Experimental study on the impact of tsunami-like waves on buildings
The influence of orientation and openings

Ylla Arbós, Clàudia; Wüthrich, Davide

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RAILDRESDEN 2025

11th International Conference on Railway Operations Modelling and Analysis

Book of Abstracts

IAROR
International Association of Railway Operations Research

TECHNISCHE UNIVERSITÄT DRESDEN

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11th International Conference on Railway Operations Modelling and Analysis (ICROMA)

RailDresden 2025

About

ICROMA

The International Conference on Railway Operations Modelling and Analysis (ICROMA) promotes interdisciplinary discussions in the railway planning and operations research area by combining the expertise of academics and professionals. ICROMA Conferences give researchers, consultants, and industrial practitioners the opportunity to meet, present their latest research, exchange know-how, and discuss current developments and applications.

The ICROMA Conferences are organized by the International Association of Railway Operations Research (IAROR) every two years since 2005. The previous conferences were held at:

- Delft University of Technology, Netherlands
- Leibniz University Hannover, Germany
- ETH Zürich, Switzerland
- University of Rome, Italy
- Technical University of Denmark, Denmark
- Chiba Institute of Technology, Japan
- IFSTTAR, France
- Linköping University, Sweden
- Beijing Jiaotong University, China
- University of Belgrade, Serbia

IAROR

The International Association of Railway Operations Research (IAROR) is a global organization dedicated to advancing research in railway operations and management. It fosters collaboration between academia and industry to develop innovative methodologies for improving railway efficiency, safety, and sustainability. IAROR organizes the prestigious International Conference on Railway Operations Modeling and Analysis (ICROMA), providing a platform for researchers and professionals to exchange ideas. Its focus areas include timetable optimization, capacity management, traffic management, network resilience, and digitalization in rail transport. Through interdisciplinary research, IAROR contributes to the development of smarter and more reliable railway systems worldwide.

Dresden University of Technology

Technische Universität Dresden (TU Dresden) is one of Germany's leading research universities and a member of the German Universities of Excellence. Founded in 1828, it is renowned for its strong interdisciplinary research, particularly in engineering, natural sciences, medicine, and humanities. With over 30,000 students and a global research network, TU Dresden fosters innovation through collaborations with industry and academia. Its cutting-edge research focuses on digitalization, materials science, energy efficiency, transport and biomedicine. The university's commitment to sustainability and technology transfer makes it a key player in shaping the future of science and industry.

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Preface

The International Conference on Railway Operations Modelling and Analysis (ICROMA) has been a key platform for the international transfer of knowledge and collaboration in railway planning and operations research. Since its inception in Delft in 2005, ICROMA has traveled across major railway research hubs, including Hannover (2007), Zürich (2009), Rome (2011), Copenhagen (2013), Tokyo (2015), Lille (2017), Norrköping (2019), Beijing (2021), and Belgrade (2023).

Now, in 2025, we are delighted to welcome you to **RailDresden 2025**, the next edition of ICROMA, hosted by **the "Friedrich List" Faculty of Transport and Traffic Sciences, TU Dresden**, in **Dresden, Germany**. Dresden, known for its rich history, cultural heritage, and strong ties to engineering and technology, provides an ideal setting for fostering discussions on the future of railway operations. TU Dresden, one of Germany's leading technical universities and a University of Excellence, has a long tradition of research in railway systems. The **"Friedrich List" Faculty of Transport and Traffic Sciences** is the largest academic institution in Germany dedicated to mobility research, making it a fitting host for this prestigious conference.

ICROMA is more than just a series of scientific conferences—it is a forum dedicated to tracking the latest advancements and inspiring future research in railway systems. We extend our gratitude to the authors who have contributed papers and posters covering a wide range of topics in railway operations, modelling, and analysis. In this edition, we received an impressive **154 paper submissions**, of which **131 papers** have been accepted following a rigorous peer-review process. Additionally, we have accepted **95 poster submissions**. We are grateful to our **Scientific Advisory Committee (SAC)**, consisting of **60 esteemed experts**, as well as our extended pool of reviewers, all of whom have played a crucial role in ensuring the high quality of the conference program.

We also express our deep appreciation to our sponsors and supporters. This conference would not be possible without their generous contributions. We extend special thanks to **Alstom**, the General Sponsor of RailDresden 2025, along with our **Gold Sponsors: Trenolab, IKOS**, and **OpenTrack Railway Technology**, as well as all other sponsors and supporters who have helped make this event possible.

With more than **350 participants** expected, RailDresden 2025 will serve as a dynamic forum for researchers, industry professionals, and policymakers to exchange ideas and explore innovative solutions for the railway sector. As we gather in Dresden in **April 2025**, we look forward to engaging discussions, insightful presentations, and fruitful collaborations that will shape the future of railway operations research.

Dresden, April 2025
On behalf of the Organizing Committee
Nikola Bešinović

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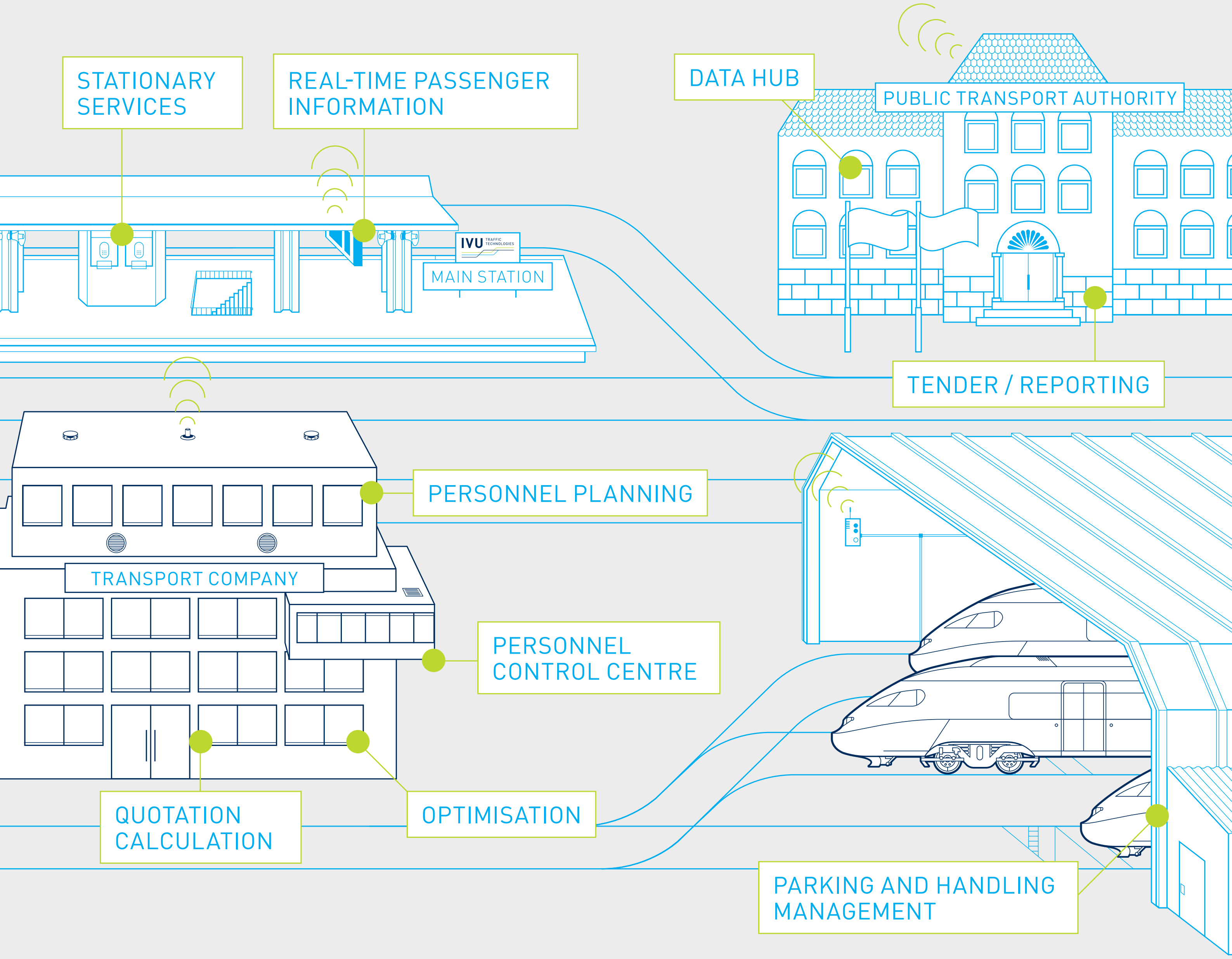

Timetable

Tuesday, 1st April

12:00pm - 1:00pm	**TUE-1-A: Lunch** Location: **POT/013/U**
1:00pm - 2:00pm	**TUE-2: Mini Course 1: Building Trust in AI: Alstom's Journey Towards New, Safe, and Reliable Mobility Solutions** Location: **POT/051/H** Session Chair: **Rob Goverde** Session Chair: **Francesco Corman**
2:00pm - 3:00pm	**TUE-3: Mini Course 2: Energy efficient train operation** Location: **POT/051/H** Session Chair: **Rob Goverde** Session Chair: **Francesco Corman**
3:00pm - 3:15pm	**TUE-3-A: Break** Location: **POT/051/H**
3:15pm - 4:15pm	**TUE-4: Mini Course 3: Spatio-temporal networks for mapping railway operations** Location: **POT/051/H** Session Chair: **Rob Goverde** Session Chair: **Francesco Corman**
4:15pm - 5:15pm	**TUE-5: Mini Course 4: Challenges and solutions of solving a large-scale networked high-speed railway disruption management problem** Location: **POT/051/H** Session Chair: **Rob Goverde** Session Chair: **Francesco Corman**
5:30pm - 7:30pm	**TUE-6: Welcome Reception** Location: **Dülfersaal, TU Dresden**

Wednesday, 2nd April

9:00am - 9:30am	**WED-1: Opening Session** Location: **POT/081/H** Session Chair: **Nikola Bešinović**
9:40am - 11:00am	**WED-2-A: Capacity** Location: **POT/051/H** Session Chair: **Nils Niessen** **WED-2-B: Rescheduling and Traffic Management 1** Location: **POT/151/H** Session Chair: **Andreas Oetting** **WED-2-C: Freight Analytics** Location: **POT/251/H** Session Chair: **Chao Wen** **WED-2-D: Maintenance and monitoring** Location: **POT/361/H** Session Chair: **Yung-Cheng (Rex) Lai**
11:00am - 12:00pm	**WED-3-A & WED-3-B: BREAK + POSTER SESSION** Location: **POT/168/S** & **POT/161/S**
12:00pm - 12:45pm	**WED-4-A: Keynote Anita Schöbel** Location: **POT/081/H** Session Chair: **Nikola Bešinović** Session Chair: **Jörn Schönberger**
12:45pm - 2:00pm	**WED-5: Lunch** Location: **POT/FOYER & POT/013**
2:00pm - 4:00pm	**WED-6-A: Timetabling and Scheduling 1** Location: **POT/051/H** Session Chair: **Dario Pacciarelli** **WED-6-B: Simulation-Based Decision Making** Location: **POT/151/H** Session Chair: **Ingo Hansen** **WED-6-C: Freight Yards** Location: **POT/251/H** Session Chair: **Ivan Belosevic** **WED-6-D: Rolling Stock and Crew Scheduling** Location: **POT/361/H** Session Chair: **Thomas Schlechte**
4:00pm - 4:30pm	**WED-7: Break** Location: **POT/FOYER & POT/013**
4:30pm - 6:30pm	**WED-8-A: Timetabling and Scheduling 2** Location: **POT/051/H** Session Chair: **Pieter Vansteenwegen** **WED-8-B: Rail Operations, Infrastructure, and Safety** Location: **POT/151/H** Session Chair: **Alex Landex** **WED-8-C: Freight Yards and Freight Flow Optimization** Location: **POT/251/H** Session Chair: **Tyler Dick** **WED-8-D: Capacity and Quality** Location: **POT/361/H** Session Chair: **John Preston**

Thursday, 3rd April

9:00am - 11:00am	**THU-1-A: Timetabling and Scheduling 3** Location: **POT/051/H** Session Chair: **Giorgio Medeossi** **THU-1-B: Rescheduling and Traffic Management 2** Location: **POT/151/H** Session Chair: **Joaquin Rodriguez** **THU-1-C: AI and Data-Driven Decisison Making** Location: **POT/251/H** Session Chair: **Thomas White** **THU-1-D: Station Capacity and Passenger Flows** Location: **POT/361/H** Session Chair: **Francesco Corman**
11:00am - 12:00pm	**THU-2-A & THU-2-B: BREAK + POSTER SESSION** Location: **POT/168/S & POT/161/S**
12:00pm - 12:45pm	**THU-3-A: Keynote Xuesong Zhou** Location: **POT/081/H**
12:45pm - 2:00pm	**THU-4: Lunch** Location: **POT/FOYER & POT/013**
2:00pm - 6:30pm	**THU-5-A: Technical Excursion 1:** DB InfraGO - Operation centre, Leipzig **THU-5-B: Technical Excursion 2:** DB InfraGO – New railway line Dresden - Prague, Heidenau **THU-5-C: Technical Excursion 3:** CargoBeamer – Test terminal, Leipzig **THU-5-D: Technical Excursion 4:** RailMaint – Maintenance site, Leipzig **THU-5-E: Technical Excursion 5:** TU Dresden – Railway Operations and Railway Signalling Laboratories, Dresden **THU-5-F: Technical Excursion 6:** Alstom Transportation – Production site, Bautzen
7:00pm - 10:00pm	**THU-6-A: Conference Dinner (special ticket required)** Location: **Am Alten Güterboden 3 / 01445 Radebeul**

Friday, 4th April

9:00am - 11:00am	**FRI-1-A: Timetabling and Scheduling 4** Location: **POT/051/H** Session Chair: **Christian Liebchen** **FRI-1-B: Disruption Management** Location: **POT/151/H** Session Chair: **Rob Goverde** **FRI-1-C: Freight Operations** Location: **POT/251/H** Session Chair: **Carlo Mannino** **FRI-1-D: Maintenance and Infrastructure Performance** Location: **POT/361/H** Session Chair: **Steven Harrod**
11:00am - 12:00pm	**FRI-2-A & FRI-2-B: BREAK + POSTER SESSION** Location: **POT/168/S & POT/161/S**
12:00pm - 12:45pm	**FRI-3-A: Keynote Arnd Stephan** Location: **POT/081/H**
12:45pm - 1:45pm	**Lunch** Location: **POT/FOYER & POT/013**
1:45pm - 3:45pm	**FRI-5-A: Line Planning** Location: **POT/051/H** Session Chair: **Lei Nie** **FRI-5-B: Rescheduling and Traffic Management 3** Location: **POT/151/H** Session Chair: **Paola Pellegrini** **FRI-5-C: Train Control and Calibration** Location: **POT/151/H** Session Chair: **Anders Peterson** **FRI-5-D: Planning and Policy** Location: **POT/361/H** Session Chair: **Alex Wardrop**
3:45pm - 4:30pm	**FRI-6: IAROR Business Meeting and Best Papers Announcement** Location: **POT/081/H** Session Chair: **Nikola Bešinović** Session Chair: **Rob Goverde**


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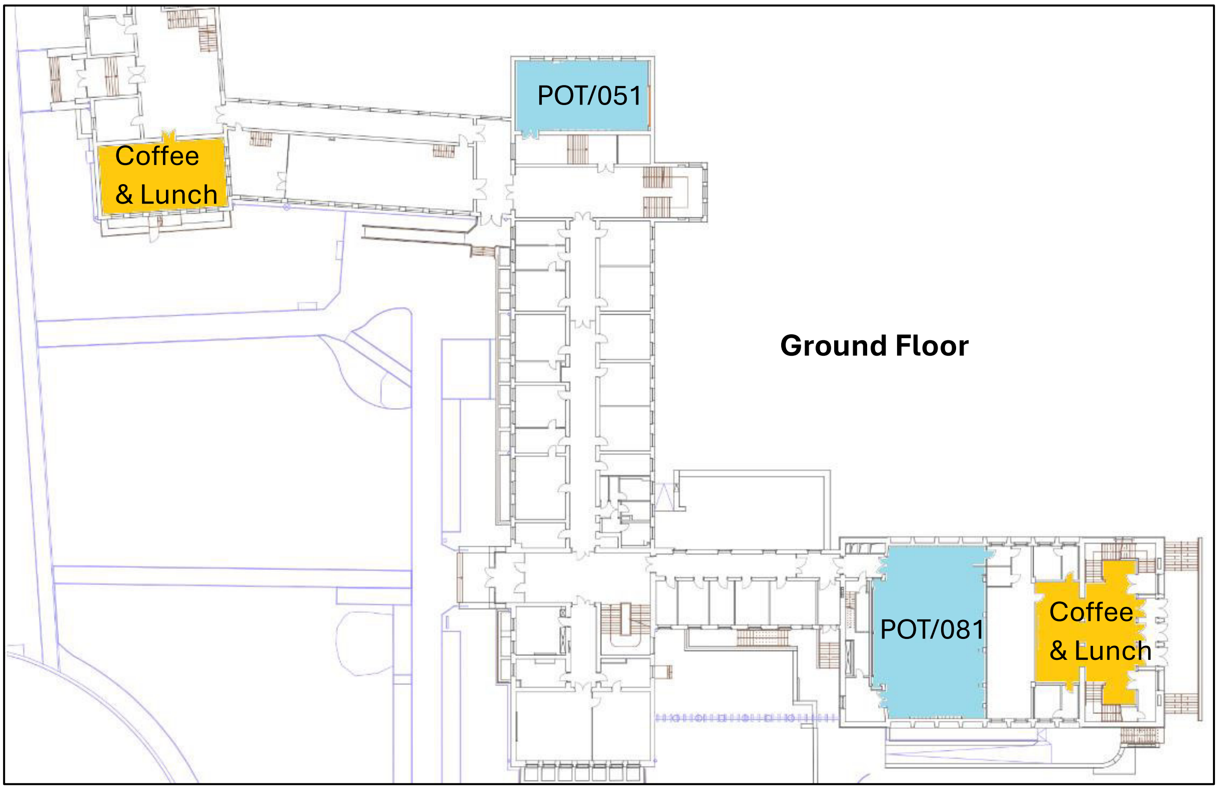
Location

RailDresden 2025 will be held at Dresden University of Technology – “Friedrich List” Faculty of Transport and Traffic Science. All activities (except for the welcome reception, conference dinner and technical visit) will take place in the faculty building, specifically:



Parallel sessions of the conference will be held in rooms

- POT/051 – Ground floor,
- POT/151 – Floor Level 1,
- POT/251 – Floor Level 2,
- POT/361 – Floor Level 3.

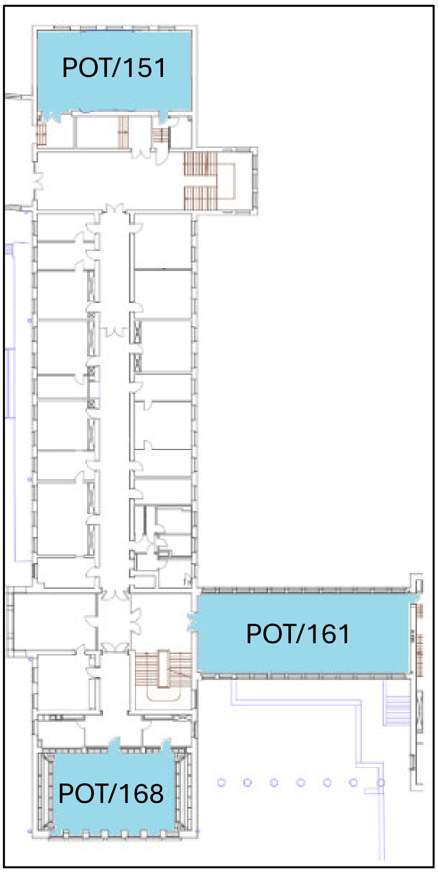
Keynote speeches and Opening will be held in room POT/081 – Ground floor & Floor Level 1.

Mini course will be held in room POT/051 – Ground floor.

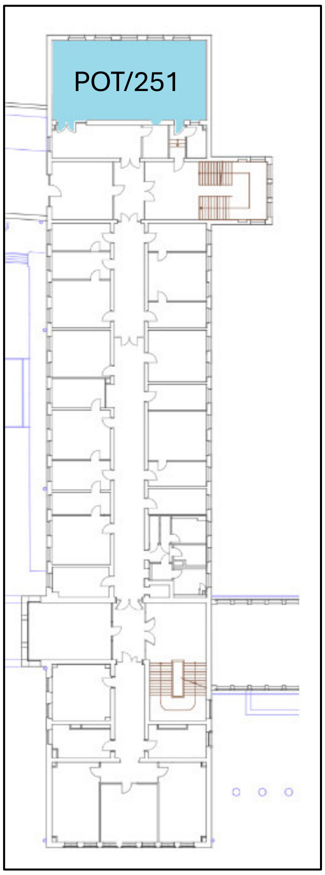
Exhibitors’ area will be located in a Foyer in front of POT/081 – Floor Level 1.

Poster presentations will be located in rooms POT/161 and POT/168 – Floor Level 1.

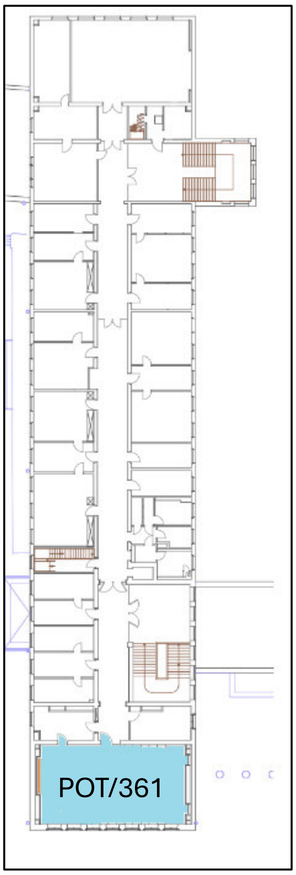
Floor Level 1



Floor Level 2



Floor Level 3



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Keynotes

Sustainable passenger rail transportation

Prof. Dr. Anita Schöbel (RPTU Kaiserslautern-Landau)

Moving travelers efficiently, with low costs, and respecting environmental goals like CO2 emissions is one of the challenging problems our society faces today. In this talk we sketch how optimization approaches can help to make our nowadays railway transportation more sustainable. A first goal is to make railway transportation more attractive for travelers, in particular more attractive than using other modes of transport such as flights or the private cars. Travelers prefer fast, reliable, safe and affordable transportation. Here we sketch research that aims at minimizing travel times and increases reliability while respecting budget constraints. In this context, we show that integrating different planning stages may help to further improve efficiency of railway transportation. A second step is to make public transport modes themselves more energy-efficient. We sketch some first ideas on how to use regenerative energy which leads to new and challenging timetable problems. The objectives in this problem are two-fold: Firstly, want to minimize the traveling times of the passengers, but, secondly, we also want to use as much regenerative energy as possible. Finally, for providing sustainable transport for the society as a whole, we cannot look isolated at railway optimization but have on the one hand to consider the first mile, and, on the other hand, we also have to look at other modes of transport besides railway transportation. We sketch a first model in which such different transport modes are considered simultaneously.

CV of Prof. Dr. Anita Schöbel

Anita Schöbel is professor for Applied Mathematics at the RPTU University of Kaiserslautern-Landau and she is head of the Fraunhofer Institute for Industrial Mathematics ITWM. The ITWM has 550 employees dealing with industrial research projects in applied mathematics with a strong focus on mobility. At Fraunhofer Society, Anita Schöbel coordinates the strategic research area Next Generation Computing and the quantum computing competence network. In 2019 and 2020 she has been president of the German Operations Research Society (GOR). Currently, she is president of EURO (Association of European Operational Research Societies). Among others, she is member of the senate of the national research data infrastructure (NFDI), and AI pilot for mobility of the state Rhineland-Palatinate (RLP). She is also a member of the council for technology of RLP. In her research, Anita focuses on discrete optimization in public transport. She has been PI in many industrial and research projects, among them the European projects ARRIVAL, EASIER and OptALI and cooperations with India. She also coordinated a research unit (Forschungsgruppe) on Integrated Transportation funded by the German Research Foundation (DFG) and currently coordinates a ministry-funded project on synchronizing different modes of transport. Anita is in the steering committees of the ATMOS and CASPT conference series. She is author of 170 refereed research articles and 9 books.

Foundations and Frontiers in Urban Rail and Freight Rail: Theoretical Advances, AI Innovations, and Future Directions for Multi-Modal Integration

Prof. Dr. Xuesong Zhou (Arizona State University)

It will highlight key optimization and simulation models that have shaped the field over the past decade and examine the transformative role of AI in enhancing infrastructure resilience, behavioral adaptation, and financial sustainability. Additionally, the talk will discuss emerging interdisciplinary opportunities, including low-altitude air mobility, underground logistics, and dynamic pricing strategies. By bridging innovations in AI, operations research, and transportation engineering, this keynote will provide a forward-looking perspective on the challenges and opportunities that will shape the future of urban and freight rail systems in an increasingly connected and autonomous transportation landscape.

CV of Prof. Dr. Xuesong Zhou

Xuesong (Simon) Zhou is a Professor of Transportation Systems at the School of Sustainable Engineering and the Built Environment, Arizona State University (ASU), Tempe, Arizona. Dr. Zhou's research focuses on advancing methodologies in multimodal transportation planning, with applications spanning dynamic traffic assignment, traffic estimation and prediction, large-scale routing, and rail scheduling. Dr. Zhou has served as an Associate Editor of Transportation Research Part C, is currently the Executive Editor-in-Chief of Urban Rail Transit, and an Editorial Board Member of Transportation Research Part B. He has also chaired the INFORMS Rail Application Section (2016 and 2025) and currently serves as a subcommittee chair of the TRB Committee on Transportation Network Modeling (AEP40). Dr. Zhou, with an H-index of 60 and 11,000 citations, leads the ASU Transportation+AI Lab, where his team developed widely-used open-source tools such as DTALite, NEXTA, and OSM2GMNS, collectively amassing over 100,000 downloads and deployments by planning agencies and DOTs. He actively fosters collaboration in the field, serving as the 2023 TRB Innovations in Travel Analysis and Planning Conference chair and as a board member of the Zephyr Foundation.

Intergenerational transport transition project: Can rail support this?

Prof. Dr. Arnd Stephan (TU Dresden)

The railroads are rightly ascribed a key role in achieving climate-friendly mobility. In order to fulfill this expectation, the railways must be upgraded consistently and quickly. This requires the modernization and expansion of the infrastructure on the one hand and the continuous procurement of new rail vehicles on the other. This is the only way to provide customers with a high-quality and reliable transport service that will remain competitive in the future. Despite great expectations for the future of the railways in Germany in terms of the transport and energy transition, the daily challenges remain enormous: large-scale corridor renovations are pending within extremely short periods of time, digitalization must be continued and, at the same time, the increasing demand for passenger and freight transport must be met in a high-quality manner.

Basically, the signs are good:

- Rail is an important and efficient sector. It has social significance.
- Rail can do "much and fast" – that is its trademark in the transport market.
- Rail is largely electro-mobile and already runs more than 90 % of the transport volume in Germany on almost 70 % renewable electricity.
- Rail has long-lasting operating resources. The capital tied up in it provides long-term benefits - it is not a throwaway society.
- Rail can relieve the noisy and hectic roads – but not replace them.
- Rail currently has strong political support.
- But: the rail is not very flexible. It hardly seems agile in the 21st century:

It all takes far too long: the decision-making process, the new construction, the approval, the changes to the existing assets – technically and operationally. And all this against a backdrop of rapid technical and social development: new forms of mobility, digital transformation, artificial intelligence, ...

We just see a decline in operating quality – at least in Germany. And this will continue for a while, as the urgently needed renovations are restricting the performance of the network. Due to 200 years of railroads, there are considerable inertia and preservations of property rights of the stakeholders. Although there is a great vision for the future of railways it is to expect that not everything will always run smoothly over the next years. We need to make good and far-sighted arguments so that society and politicians continue to support and fund the expansion of the railways. The presentation highlights the current challenges facing the railroads in Germany and outlines the prospects for the future.

CV of Prof. Dr. Arnd Stephan:

1985 – 1990: studies in electrical engineering / electrical railways at University for transportation and traffic sciences „Friedrich List“ Dresden, 1990 – 1993: PhD at TU Dresden, 1995: doctorate , 1993 – 2008:project engineer, senior expert, head of branch office and authorized officer, IFB Institut für Bahntechnik GmbH, Dresden, since 1995: approved expert by German Federal Railway Authority EBA for electrical power supply installations and MAGLEV technology, since 2004: Managing Director of Competence Center for High Performance Rail Systems at TU Dresden, since 2008: Full Professor at TU Dresden for Electric Railways, since 2012: Managing Director of IFB Institut für Bahntechnik GmbH, Berlin and Dresden, since 2020 Chairman of the Board of German Railway Cluster Rail.S e.V.

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Mini Courses

Building Trust in AI: Alstom's Journey Towards New, Safe, and Reliable Mobility Solutions

Nenad Mijatovic
Alstom group; nenad.mijatovic@alstomgroup.com

As aspiring professionals in the rail industry, you are entering a field ripe for transformation through technology. While AI applications in mobility have largely focused on non-safety-critical aspects, we stand on the brink of a revolution in safety-critical applications such as autonomous trains and advanced signalling systems. In this session, Nenad will explore how Alstom is leading the charge in building trust in AI. He will discuss the critical importance of integrating AI safely into safety-critical systems and share innovative use cases tailored for the rail sector. Learn about an AI solution that detects failures in radio communication—vital for safe train operations—and discover how smart troubleshooting systems leverage predictive maintenance and human-centric AI technologies, including Large Language Models (LLMs), to empower engineers in swiftly diagnosing and resolving system issues. Join us for an interactive session that not only showcases Alstom's commitment to trustworthy AI solutions but also prepares you for the exciting advancements that lie ahead in the rail industry. Together, we can harness the power of AI to shape a safer and more efficient future for mobility.

Energy efficient train operation

Pengling Wang
Tongji University, China, People's Republic of; pengling_wang@tongji.edu.cn

This mini-course presents the fundamental theories, state-of-the-art models and algorithms for the energy efficient train operation. Energy and environmental sustainability in transportation have received increasing attention in recent decades. Railway, as one of the most energy-efficient transport, plays an essential role in improving the world's energy and environmental sustainability. The energy consumption of a railway system is composed of many parts, among which, traction energy consumption accounts for about 80% of the total energy consumption of the railway system, which is the main focus of energy conservation research. In this mini-course, we will focus on the fundamental methods for saving traction energy consumption and improving the usage of regenerative energy. The course discusses timely topics such as energy-efficient train trajectory optimization, energy-efficient timetable optimization, regenerative braking energy utilization improvement, integrated train rescheduling and train control, etc. The course also presents a few research case-studies to demonstrate concepts and showcase potential applications.

Spatio-temporal networks for mapping railway operations

Deb Panja
Utrecht University; d.panja@uu.nl

Propagation of delays in railway systems — a complex system — is an emergent phenomenon that vary dramatically over space and time, making it challenging to predict future system trajectories at "macro", system-level scales. Spatio-temporal variations in delays at the macro-scale stem from spatial and temporal heterogeneities in their generating mechanisms at the ``micro'' scales; i.e., from the heterogeneities in the location, timing, and nature of physical interactions among system actors: scheduled services, rolling stocks and crew in the case of railways. We develop spatio-temporal networks as a details-driven and data-compatible framework for unravelling spatio-temporal variations in emergent dynamics of real-world complex systems, and use railways as an application area to demonstrate the efficacy of the framework: which bottlenecks in a railway system can be anticipated. We will demonstrate how the framework may prove to be significantly advantageous in unravelling spatio-temporal development of delays in railway systems.

Challenges and solutions of solving a large-scale networked high-speed railway disruption management problem

Lingyun Meng, Dr. Zhengwen Liao
Beijing Jiaotong University, China, People's Republic of; lym@bjtu.edu.cn

In high-speed railway operations, unavoidable perturbations such as infrastructure failures and adverse weather conditions often occur, leading to delays and even service cancellations. Effective railway traffic management is essential for minimizing these impacts and improving service punctuality and reliability. This requires efficiently rescheduling trains while managing various resource constraints such as tracks and rolling stock, ensuring smooth and reliable operations even in the face of unforeseen disruptions. This lecture introduces a multi-solution approach to solve multi-granularity problems in high-speed railway disruption management. We examine tailored solutions to three key challenges: 1) complex railway terminals; 2) dense railway corridors; and 3) large-scale railway networks. By applying advanced optimization models and strategies, the lecture will demonstrate how these solutions can enhance system efficiency during disruptions. The conclusions will highlight the practical relevance and real-world applicability of these solutions in improving railway operations.

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List of Abstracts

WED-2-A: Capacity

Time: Wednesday, 02/Apr/2025: 9:40am - 11:00am
Session Chair: Nils Niessen

Railway nodes in an integrated timetable-based network capacity assessment model

Cédric Kekes[1], Franziska Theurich[1], Karl Nachtigall[1], Sara Comelli[2], Norman Weik[2]
[1]Chair of Traffic Flow Sciences, TU Dresden, Germany; [2]Professorship of Design and Operation of Public Rail Transport Systems, TUM, Germany; cedric.kekes@tu-dresden.de

In this paper, we show an approach to integrate nodes into a timetable-based network capacity model, where the residual freight capacity is computed for a given passenger timetable. Since timetable-based capacity assessment suffers from fluctuating freight traffic demand, pre-constructed slots on net segments and nodes are used which will be combined to freight train paths for a certain demand. An evaluation, using a (max,+)-approach, of resulting slots and timetables ensures that they are robust against delays and provide an acceptable level of service. As capacity assessment relies on an accurate modelling of the infrastructure of railway nodes, a sufficient level of accuracy must be derived. In this paper, it is shown that publicly available open data sources contains the necessary information. Based on the provided layout of railway nodes with all tracks, switches and signals, further relevant information can be deduced, as turn restrictions or the number of siding tracks for freight trains. With it, we are able to construct feasible slots and train paths in and through railway nodes. This allows for a network-wide capacity assessment. Moreover, the approach allows for consideration and modelling of different signalling and train control equipment and is flexible to allow data enrichment from other sources. The integrated model is applied in a case study on a railway node and its adjacent lines in Northern Germany to evaluate its effects

The influence of the structure of timetable concepts on the capacity of rail corridors

Martin Johannes Tosstorff, Daniel Heitzinger, Norman Weik
Technische Universität München, Germany; martin.tosstorff@tum.de

Railway timetabling in multiple countries in Europe is seeing a shift of focus from optimally considering train path requests by competing operators to a more strategic view aiming to coordinate trains and connections in railway nodes to allow for seamless freight logistics chains and passenger transfers. This yields a change of the structural properties of railway timetables introducing new constraints on the train sequence and spacing on railway corridors. In this paper we analyze the effects of structural parameters of timetables on the capacity of rail corridors. A timetable ensemble generation allowing to study different timetable types is developed, features of timetables relating to structural properties are defined, and the resulting timetables are analyzed with respect to the expressiveness and impact of features on timetable stability using monotony criteria and random forest-based regression analysis. It is found that timetable margins are, by far, the most decisive factor for stability, followed by shortest headways and corresponding buffers and average traveling speed, suggesting a stronger focus on timetable margins in capacity planning approaches for highly structured timetables.

Railway capacity utilization optimization with skip-stop planning in a minimum cycle time calculation model

Huaibin Hu[1,2], Huiling Fu[1,2], Xin Zhang[3], Siqi Zhang[2], Lei Nie[1,2], Lu Tong[1,2]
[1]Frontiers Science Center for Smart High-speed Railway System, Beijing Jiaotong University, Beijing 100044, China; [2]School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China; [3]Transportation & Economics Research Institute, China Academy of Railway Sciences Corporation Limited, Beijing 100081, China; 20114038@bjtu.edu.cn

Given a line plan, the minimum cycle time of the resulting train timetable serves as a critical measure of railway capacity. Traditional capacity analysis approaches typically take a fixed line plan to generate cyclic train timetables and determine the minimum cycle time. In this paper, we integrate train stop adjustments into cyclic timetable generation and propose a capacity utilization optimization approach where the concluded train stop plan and timetable can achieve a high level of railway capacity utilization, i.e., the minimum cycle time. Based on the Periodic Event Scheduling Problem (PESP) framework, we formulate a multi-objective linear programming model for minimum cycle time calculation (MCTC) considering skip-stop planning (skipping or adding stops), with objectives of minimizing the cycle time, stop adjustments, and travel time of all trains. The model involves decisions on the cycle time, train stop adjustments, as well as arrival and departure times, and accounts for service frequency requirements of passenger origin-destination pairs (ODs) and the distribution of train stops to mitigate the impact of skip-stop planning on passenger service quality and operation feasibility. An iterative approximation (IA) approach is designed to handle complex instances. Taking the Jinghu high-speed railway (HSR) line as the case study background, both small-scale and real-world cases demonstrate that skip-stop planning further reduces the cycle times compared to fixed line plans while maintaining OD service frequency requirements.

The relationship between station capacity utilization and knock-on delays

Fabrizio Cerreto[1], **Victor Flensburg**[2]

[1]The Copenhagen Metro; [2]Banedanmark; fac@m.dk, jvfl@bane.dk

Railway stations often represent critical bottlenecks within the transportation network, influencing both the capacity and stability of rail operations. This study investigates the complex interplays between station capacity consumption and operational stability to elucidate how traffic plans and station layouts impact punctuality. Utilizing a probabilistic approach to analyze various hypothetical traffic plans, this research explores the impact of the station on train punctuality, assessing the capacity consumed and subsequent effects on service reliability. The novel findings suggest an intricate relationship between station capacity usage and the resulting knock-on delays across two rather different Danish stations, Copenhagen Central and Ringsted, over an eight-year period, correlating higher capacity utilization with increased entry perturbations. This study infers knock-on delays from historical timestamps at arrival and departure and refines the conventional understanding of station capacity's direct impacts but also offers a methodology for predicting the implications of future traffic volumes. This research contributes to the strategic planning of railway operations, providing output that can easily be turned into economical values for Cost Benefit Analyses in the evaluation of future investments.

WED-2-B: Rescheduling and Traffic Management 1

Time: Wednesday, 02/Apr/2025: 9:40am - 11:00am
Session Chair: Andreas Oetting

A Self-organized Approach for Real-Time Railway Timetable Rescheduling

Konstantinos Rigos, Egidio Quaglietta, Rob M.P. Goverde
TUDelft, Netherlands, The; k.rigos@tudelft.nl

Effective rail traffic management is necessary to mitigate the impact of unforeseen train service disturbances. Traditional decomposition methods, while effective in managing complexity, often struggle to maintain global optimality and real-time responsiveness. In this paper, we propose a novel approach that decomposes the rescheduling problem by means of a self-organising paradigm where trains are intelligent autonomous agents deciding on their decisions after reaching a consensus. The proposed Self-Organized Train Rescheduling (SOTR) algorithm is inspired by the Distributed Constraint Optimization Problem (DCOP) framework. This algorithm treats trains as intelligent agents capable of constructing their own traffic plans, communicating with neighbouring agents, and making decisions that lead to an optimal timetable. Each train, acting as an agent, assesses its situation, predicts conflicts, and negotiates with other trains to find the most efficient solution in regard to total delay. This distributed decision-making process allows for rapid adaptation to dynamic disturbances and ensures scalability to large networks. We validate the effectiveness of our approach by using a micro-simulation tool, demonstrating its ability to minimize secondary delays and maintain network continuity in perturbation scenarios.

Learning to Platforming: A Deep Reinforcement Learning Method for the Train Platforming and Rescheduling Problem

Hongxiang Zhang[1], Yongqiu Zhu[2], Liuyang Hu[1], Andrea D'Ariano[3], Yaoxin Wu[4], Gongyuan Lu[1]
[1]Southwest Jiaotong University, China, People's Republic of; [2]Department of Transport and Planning, Delft University of Technology, the Netherlands; [3]Department of Civil, Computer Science and Aeronautical Technologies Engineering, Roma Tre University, Italy; [4]Department of Industrial Engineering & Innovation Sciences, Eindhoven University of Technology, The Netherlands; hongxiang@my.swjtu.edu.cn

This paper proposes the Learning to Platforming (L2P) method, a novel graph neural network based deep reinforcement learning method, to solve the Train Platforming and Rescheduling Problem (TPRP). We customize a Markov decision process (MDP) to formulate the solving process of TPRP, utilizing a graph structure to represent states of trains, routes, and berthing tracks from a microscopic perspective. Then, we design a hybrid graph neural network named hAI-GNN to learn informative node embeddings on the graph encoded state. These embeddings are utilized to derive an effective action from the lightweight action space of MDP, which is associated with the decision object train under the state. A discrete-event simulation model is employed to serve as the environment of MDP and implement state transition mechanism. The hAI-GNN based policy network is trained by the Proximal Policy Optimization (PPO) algorithm with the reward function designed to minimize total knock-on delay trains and platform changes. The experiments on real-world instances show that the proposed L2P method can obtain high-quality solutions for both small and large scale instances within very short solving times.

Potential analysis and recommendations for self-organising rail traffic management

Egidio Quaglietta[1], Paola Pellegrini[2], Vito Trianni[3]
[1]Delft University of Technology, Netherlands, The; [2]University Gustave Eiffel, COSYS-ESTAS; [3]Institute for Cognitive Sciences and Technologies, CNR; e.quaglietta@tudelft.nl

Railways are in need of technological and operational enhancements to achieve the EU strategic vision of a sustainable, integrated transport system. Beside the deployment of digital signalling and automatic train operations, advanced rail traffic management is critical to increase rail transport capacity and provide a seamless intermodal integration. To this aim, the concept of self-organisation has been recently proposed, which involves intelligent trains to autonomously decide and locally negotiate optimised traffic strategies. Although science considers self-organisation key to an efficient flexible rail service, the view of the industry is still unclear. Characterising the industrial perspective is instead essential to evaluate investment and migration plans of future rail developments. This paper addresses such a need by a multi-target Delphi analysis outlining an expert perspective on current traffic management gaps, potentials of self-organisation as well as critical steps and recommendations enabling a paradigm migration. Analysis results indicate that the state-of-practice is limited by technological and legal barriers to transport data sharing, slow rail digitalisation and organisational separation between infrastructure and operations. Traffic self-organisation could overcome current limitations only if it fosters digitalisation, a cooperative business model and policies for intermodal planning and data sharing. The rail market could be expanded by easier investor accessibility and a more attractive demand-effective intermodal rail service. Stakeholders' reluctance in approving novel business models, policies and rules is however a threat to this paradigm. Feasibility studies, round-tables and joined sector actions are recommended for defining policies, proof-of-concepts and plans for migrating to a self-organising rail traffic.

Resource-based Integrated Train Rescheduling and Rolling Stock Circulation Replanning under Different Rolling Stock Usage Rules

Ranfei Zheng[1], Lingyun Meng[1], Xiaojie Luan[1], Jianrui Miao[1], Zhengwen Liao[1], Valentina Cacchiani[2], Feng Ran[3]
[1]School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China; [2]DEI, University of Bologna, Bologna I-40136, Italy; [3]Tianjin Hub Loop Railway Co.,Ltd. , Tianjin, China; 22110264@bjtu.edu.cn

Real-time railway operations often face unexpected severe disruptions, necessitating train rescheduling to reorganize operations and minimize negative impacts. Flexible adjustments to rolling stock circulation can reduce train delays and cancellations. However, different scenarios impose various constraint rules on rolling stock circulation adjustments. For example, the common rules of rolling stock circulation, ranging from the most fixed to the most flexible, can be divided into three types: fixed turning, quasi-flexible turning with restriction on vehicle types, and flexible turning. Applying unnecessarily strict rules can lead to avoidable delays that could have been mitigated through more flexible turning rules of rolling stock. Conversely, overly flexible rules may result in rescheduled timetables that are infeasible in practice. Therefore, advanced rescheduling methods that can describe different turning rules of rolling stock are desired.This paper focuses on the integrated optimization of train rescheduling and rolling stock circulation planning under severe disruption including section blockage and electrical power reduction. We propose an innovative resource-based time-space network and then construct an integer programming model. The model is designed to flexibly adapt to various rolling stock usage rules. To achieve solutions, we developed a Lagrangian relaxation decomposition framework along with an innovative dynamic priority-based heuristic algorithm. In the heuristic algorithm, customized connection and improvement strategies are designed to promote solution quality and efficiency. The effectiveness and efficiency of the proposed approach is validated using a large-scale instance, including 410 trains and 161 vehicles on a 1318 km railway line.

WED-2-C: Freight Analytics

Time: Wednesday, 02/Apr/2025: 9:40am - 11:00am · *Location:* POT/251/H
Session Chair: Chao Wen

Towards transparent operations: Data-driven monitoring and assessment of industrial railways

Moritz Ruf, **Stefan Stoimenov**, **Tobias Pollehn**
ITORA GmbH, Germany; moritz.ruf@itora.de

The project RP2 (Retrieving Process Data from Position Information) is a collaborative endeavor between ITORA GmbH and the railway undertaking Mitteldeutsche Eisenbahngesellschaft mbH and was funded by the German Federal Ministry for Digital and Transport. The aim of RP2 is to enhance business intelligence through advanced data analysis of GPS data from locomotives in industrial railways. This project leverages machine learning techniques to analyze the movement patterns and operational processes of locomotives. By examining GPS data and integrating shunting data from existing IT systems, the project seeks to identify key operational parameters and insights, which can be exploited to optimize both infrastructure usage and locomotive performance. The integration of machine learning algorithms allows for the recognition of complex patterns and predictive analytics, thereby enabling practitioners to make data-driven decisions, e.g., on infrastructure maintenance dependent on usage. Tailored dashboards aggregate and facilitate the access to complex data structures. The expected outcomes include improved transparency on both operations and costs. The project RP2 contributes to the methodological field in rail freight providing a robust framework for the exploitation of GPS and shunting data to yield actionable business intelligence. As the quality of input data in railroad operations is often in need of improvement, this project is pioneering in terms of data enhancement and linking several independent data sources

Analysis of Factors Influencing the Uncertainty of Freight Train Running Time on Section Based on XGBoost-SHAP Method

Ruyue Zhao[1], **Lingyun Meng**[1], **Marcella Samà**[2], **Qi Zhang**[1], **Jianrui Miao**[1], **Xiaojie Luan**[1], **Zhixin Guo**[1]
[1]School of Traffic and Transportation, Beijing Jiaotong University, 100044, Beijing, P.R. China; [2]Department of Civil, Computer Science and Aeronautical Engineering, Roma Tre University, 00146, Rome, Italy; ruyuezhao@bjtu.edu.cn

Due to the multiple influence factors in the process of freight train operation, the freight train running time exhibits high uncertainty. Therefore, clarifying and analyzing the features importance and mechanism of the influencing factors is the primary task for accurately calculating the freight train running time. This paper selected five key influencing factors of freight train running time, including total train weight, net cargo weight, total train length, wind speed, and visibility. An XGBoost based model is developed and trained for analyzing feature importance of factors influencing running time of freight trains on sections. The interactive effects of the feature values of each influencing factor on freight train running time are studied. The experimental results indicate that the total train weight contributes the most to the freight train running time, while net cargo weight, total train length, wind speed, and visibility all show varying degrees of influence on the running time. However, the relationships between those features and the running time are nonlinear. Finally, using the random forest and neural network models as additional comparative experiments, it is found that the XGBoost model we developed has the best generalization ability and is highly efficient in training time. It performs better in understanding the interaction of key influencing factors and analyzing feature importance. Through the data-driven understanding of the factors that impact uncertainties on freight train running time, this study establishes a basis for enhancing the robustness of freight train operations and improving the quality of freight transport services.

A New Approach for Hazardous Materials Car Placement in Shunting Yards

Mehdi Fallahi[1], **Morteza Bagheri**[2], **Francesco Corman**[3]
[1]School of Industrial Engineering,Iran University of Science & Technology; [2]School of Railway Engineering,Iran University of Science & Technology; [3]Institute for Transport Planning and Systems, ETH Zürich; mehdi_fallahi@ind.iust.ac.ir, morteza.bagheri@iust.ac.ir, francesco.corman@ivt.baug.ethz.ch

The transportation of hazardous materials (hazmat) by rail introduces significant safety risks, particularly through derailments, which can lead to catastrophic outcomes such as fires, the release of toxic chemicals, and widespread environmental damage. Optimizing hazmat car placement within train consists is crucial to mitigate these risks. This paper proposes an innovative optimization model for hazmat car placement in shunting yards, integrating risk assessment with operational constraints. Utilizing integer programming, the model assigns cars to positions to minimize the overall derailment risk, drawing on historical derailment data, including causes, frequencies, and severity of past incidents. It also balances risk minimization with shunting complexity by imposing constraints on allowable maneuvers to maintain yard efficiency. An incompatibility matrix ensures regulatory compliance for safe placement of different hazmat categories. A case study demonstrates the model's effectiveness in enhancing rail safety by offering an effective framework for optimizing hazmat car placement under real-world conditions.

Data-Driven Evaluation of Freight Train Formation Complexity Using Entropy Approach

Daniel Haalboom, Uwe Höppner, Nikola Besinovic
TU Dresden, Germany; jelle_daniel.haalboom@tu-dresden.de

Rail freight is of key importance to reduce GHG emissions associated with transportation. In order to increase capacity required for a modal shift to rail, scarce resources have to be utilised in an efficient manner, while still meeting the requested level of service. Within the rail freight network, classification yards play a key role in Single Wagonload transportation. To improve the efficiency of the SWL network and meet customer demands, understanding of yard operations is of importance. Thus, planning stages of classification yards need to be based on actual dispatching data. To that end, we evaluate train formation complexity using a car set graph of shunting movements in a rail yard based on dispatching data. Based on the set graph, we propose a framework to express the train formation complexity as the entropy evolution over time of a set of cars based on a reference state. Furthermore, we describe the infrastructure capacity usage on a train level. The results show for synthetic instances of classification yards the applicability to evaluate train complexity for a variety of outbound train formations.

WED-2-D: Maintenance and monitoring

Time: Wednesday, 02/Apr/2025: 9:40am - 11:00am · *Location:* POT/361/H
Session Chair: Yung-Cheng (Rex) Lai

A Beam Search for the rolling stock corrective maintenance scheduling

Tom Ray[1,2], Ronan Bocquillon[1], Vincent T'kindt[1]

[1]Laboratoire d'Informatique Fondamentale et Appliquée de Tours (LIFAT), France; [2]SCNF Voyageurs, direction du matériel, pôle télédiagnostic cluster ouest; tom.ray@univ-tours.fr

For railway companies, rolling stocks are critical resources that need to be exploited at their maximum potential in order to respond to the transportation demand. Maintaining such fleets of trains is a very difficult task as their availabilities are very constrained. The moment and the place to fix a detected malfunction, while keeping the transportation plan stable for the users, is not an easy task, given that there may be multiple problems throughout the network. Deciding of the maintenance requests the resolution of a scheduling problem. The goal of this research is to provide an efficient solution to this problem. To achieve this, we develop a beam search, a fast tree search based heuristic able to provide quality solutions while having computation times compatible with the operational planning phase.

RADIUS: Railway signalling asset monitoring using UAS

Manuel Oñate[1], Gonzalo Oñate[1], Iciar Díaz de la Peña[1], Irene Buselli[2], Luís Rolo Mestre[3]

[1]EuroUSC España, S.L., Madrid, Spain; [2]Zenabyte s.r.l., Geneva, Italy; [3]Infraestruturas de Portugal, IP SA, Lisbon, Portugal; manuel.onate@eurousc.es

Railway signalling assets monitoring is based on three alternative methods: a) human inspection, b) wired solutions, and c) monitoring trains. These methods impose severe limitations in terms of safety issues, initial investment, complexity, operating costs, limited diagnostic data, and track occupation. The result of these limitations is that the maintenance activities of railway lines are sub-optimal, resulting in preventable failures that require expensive and disruptive reparations that imply the temporal interruption of the servicein the affected tracks. The project ”Railway digitalisation using drones” (RADIUS) proposes the use of Unmanned Aircraft Systems (UAS) to execute a large part of the inspection and maintenance tasks of signalling assets that improve on the current methods but require compliance with aviation standards and regulation besides those existing in the railway environment. To attain this goal, RADIUS has analysed the needs of the end users, to establish the system requirements, focusing its research in the communication links between the different elements of the solution, signalling asset modification to interact with the UAS, and image processing to process the visual information gathered by the UAS. A custom docking station was created to extend the range and ensure commercial viability of the solution. The individual elements and the solution as a whole have been validated in a railway relevant environment. The result of the project has been satisfactory, paving the way for the use of DRONE technology in the railway sector.

Scalable, Technology-Agnostic Diagnosis and Predictive Maintenance for Point Machine using Deep Learning.

Ruixang Ci[2], Eduardo Di Santi[1], Nenad Mijatovich[1], Clement Lefebvre[1], Michele Pugnaloni[1], Jonathan Brow[1], Victor Martin[1], Kenza Saiah[1]

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The Point Machine (PM) is a critical piece of railway equipment that switches train routes by diverting tracks through a switchblade. As with any critical safety equipment, a failure will halt operations leading to service disruptions; therefore, pre-emptive maintenance may avoid unnecessary interruptions by detecting anomalies before they become failures. Previous work relies on several inputs and crafting custom features by segmenting the signal. This not only adds additional requirements for data collection and processing, but it is also specific to the PM technology, the installed locations and operational conditions limiting scalability. Based on the available maintenance records, the main failure causes for PM are obstacles, friction, power source issues and misalignment. Those failures affect the energy consumption pattern of PMs, altering the usual (or healthy) shape of the power signal during the PM movement. In contrast to the current state- of-the-art, our method requires only one input. We apply a dense autoencoder that detects changes in the power signal pattern followed by a deep classifier to identify the failure type. Finally, a deep neural network estimates the severity of the failure, making the method compliant with the ISO-17359 standard. Our methodology is generic and technology-agnostic, proven to be scalable on several electromechanical PM types deployed in both real-world and test bench environments. The result indicates >96% accuracy onanomaly detection with negligible false positives (<0.4%), near perfect anomaly classification (>99.9%) and <1% mean absolute error for severity estimation. Finally, by using conformal prediction the maintainer gets a clear indication of the certainty of the system outputs, adding a confidence layer to operations.

Prescriptive Maintenance of Track Circuits in a Subway Environment using Artificial Intelligence

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Track circuits are an essential component of modern metro systems. They form part of the signalling system, which ensures the safe and efficient movement of trains. A track circuit detects the presence or absence of a train on a specific section of the track, enabling the signalling system to manage train movements, prevent collisions, and maintain safe distances between trains. Their correct and prompt maintenance is therefore essential to guarantee safety, reliability, and efficiency of the line. While some automated tools are often used to generate a theoretical schedule of maintenance, by now the entire planning procedure strongly relies on operators' expertise and work, since they need to combine the given plan with all the incidental real-world constraints (e.g., operations of other departments on the line, changes in priority of the interventions, occurrences of failures). Indeed, while some data-driven models are sometimes used to predict the duration of a maintenance or the expected life of an asset, they hardly contribute to the planning phase. This work proposes a twofold approach: first of all, a predictive-analytics phase able to estimate the assets' status and the restoration time and cost is developed; then, we propose an Artificial-Intelligence-based planner able to exploit at the same time all the data coming from the system, including line occupancies and intervention schedules, to automatically generale a maintenance plan. Results on real data coming from a portion of an Italian Metro support our proposal and demonstrate its effectiveness.

WED-6-A: Timetabling and Scheduling 1

Time: Wednesday, 02/Apr/2025: 2:00pm - 4:00pm · *Location:* POT/051/H
Session Chair: Dario Pacciarelli

Benders decomposition for passenger-oriented train timetabling with hybrid periodicity

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With its service regularity and well-planned train connections, periodic timetable has been widely applied in passenger railways. However, fluctuations in passenger demand call for different train services in different periods of a day, thus requiring the periodic timetables to be adjusted accordingly. This study considers a hybrid periodic timetabling problem that takes into account adjustment of periodic timetable, insertion of aperiodic train services and circulation of rolling stock units. Passenger routing is integrated in the problem to guide the planning decisions towards a passenger-oriented objective. Utilizing a hybrid time-space network representation, the problem is formulated as a service network design model with asset management and capacity constraints. To solve such a complex model in real-world instances, we propose a decomposition-based algorithm integrating Benders decomposition and column generation, where some accelerating techniques are implemented. Numerical experiments on both small- and large-scale instances show the effectiveness of the algorithm, as well as the benefits of hybrid periodic timetables in terms of reducing passenger travel costs.

Multi-period railway timetabling to serve time-dependent demand

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Passenger railway demand fluctuates daily, peaking at the start and end of the workday due to commuting to school and work. During the off-peak the volumes drop and most people travel for other purposes, like leisure and social visits, which results in different travel destinations. Despite this, many European Railways use fixed line plans and cyclic timetables that remain constant throughout the day. While this approach makes schedules easy to remember and provides ample off-peak travel options, it is primarily designed for peak-hour demand, making it less efficient. Furthermore, due to the different mix of travel purposes, a schedule based on peak-hour demand is not necessarily optimal for off-peak demand. This paper aims to combine the benefits of a cyclic timetable with the flexibility of an acyclic timetable in order to follow the time-dependent demand more closely. We propose a mixed-integer linear programming model that finds a timetable for a day consisting of several periods which each have its own line plan. The resulting timetable is required to be cyclic within each period and provide a good transition between the periods. The model is successfully tested on a case study with changing stopping patterns using data from the Dutch railway network, for which an optimal timetable is found. In this timetable, the transition between cyclic schedules can be done without cancelling trains or shifting trains from the new cyclic times.

A Lagrangian relaxation-based approach for integrated optimization of line planning and additional trains scheduling

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For busy high-speed railway lines, it is highly challenging to frequently make large-scale

adjustments to the train timetable in response to fluctuating transportation demands, especially passenger demand. Therefore, a common approach is to schedule additional trains into a pre-established base timetable. Most existing studies have either focused on finding paths for freight trains within a predominantly passenger train timetable or on optimizing the high-speed railway base timetable, often simplifying or overlooking passenger demand. This paper addresses the integrated optimization of line planning and additional trains scheduling problem by proposing a multi-objective integer linear programming (ILP) model. To solve this large-scale problem efficiently, a Lagrangian relaxation-based approach is employed, decomposing the original problem into a line planning subproblem and an additional trains scheduling subproblem, which are solved iteratively using a commercial solver and a forward dynamic programming algorithm, respectively, to obtain both the primal and dual solutions. Large-scale case studies based on the Beijing-Shanghai high-speed railway corridor demonstrate the effectiveness of the proposed model and algorithm. Experimental results show that, compared to a sequential approach, our proposed algorithm improves the objective value by an average of 3.67%.

A Fragility-based Approach to Timetable Design

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To proactively manage disturbances in railway systems, it is crucial to design robust timetables that can effectively absorb secondary delays. In practice, when route planners are tasked to produce a robust timetable, they usually start from an existing timetable and follow a complicated, iterative, and time-consuming trial-and-error process to build a new one. Given the increase in traffic demand, decision support systems are becoming essential to guide practitioners through this complex task, regardless of their experience. While several robustness measures have been proposed in the last few years, many overlook the impact of dispatching decisions on knock-on delays, limiting their real-world applicability. In this work, we introduce a fragility-based approach to timetable design, inspired by the concept of fragility recently proposed by Tessitore et al. (2024). Our approach focuses on identifying and addressing the most critical sections of the timetable to enhance the overall robustness. Specifically, we show how timetable fragility can be actually exploited by route planners to design new and more robust timetables. We propose a MILP model that aims to enhance timetable robustness by focusing on its most critical part. Considering real-life scenarios from a Norwegian railway line, our approach demonstrates the ability to enhance timetable robustness, even when employing conservative strategies for potential improvements.

Optimizing Periodic Stability in Railway Timetables: A Microscopic Model for Networks with a Macroscopic Comparison

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We present a novel microscopic model for railway timetabling designed to maximize periodic stability in mixed single- and multi-track networks. Unlike conventional approaches based on the Periodic Event Scheduling Problem (PESP), our model provides a detailed infrastructure representation with flexible routing and nuanced conflict resolution, enhancing adaptability to real-world constraints and facilitating practical implementation by operators. To ensure scalability, we integrate a Satisfiability Modulo Theories (SMT)-based approach, which efficiently narrows feasible cycle time bounds, enabling the model to handle large-scale networks. Validated on operational data from the Rhätische Bahn network—a Swiss railway with complex infrastructure—the microscopic model consistently yields lower minimal cycle times than its macroscopic counterpart. The comparative analysis also offers insights into the trade-offs between model detail, computational efficiency, and achievable cycle times across diverse operational scenarios. These findings underscore the importance of infrastructure abstraction and the careful consideration of operational and commercial interdependencies for optimal stability in complex railway networks.

Optimization of Adding Additional Train Paths for High-speed Railway Hub Loop

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This study focuses on operating public transit trains on high-speed railway hub loops to serve commuter and transfer passengers. Considering the original train operation scheme, working diagram, and EMU (Electric Multiple Unit) route crossings at high-speed railway hubs, the operation scheme, working diagram, and EMU route crossings for new loop public transit trains are determined. A feasible scheme for operating public transit trains under certain service level conditions is discussed. Aiming to improve the operating time of loop EMUs, and considering factors such as routes at stations and track utilization, an optimization model for the loop train operation plan in high-speed railway hubs is constructed. An efficient metaheuristic, MEA (Micro-Evolutionary Algorithm), based on the extraction of dominant gene structures and evolutionary mechanisms, is designed to solve the problem. The computational results show that the established model and algorithm can flexibly consider the utilization of various types of hub loop train operation plans, fully tapping into the transport potential and promoting the realization of efficient public transit operations. The results provide transportation organization plans for implementing the public transit operation of EMUs in high-speed railway hub loops.

Time: Wednesday, 02/Apr/2025: 2:00pm - 4:00pm · *Location:* POT/151/H
Session Chair: Ingo Hansen

Analysis and Modelling Performances of SC (Super Conducting) Maglev Line

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The Maglev systems are characterised by their infrastructural, technical/technological, operational, economic, social, environmental, and policy performances. These can be represented by the indicators reflecting the main stakeholders' preferences. The analytical models of indicators of these performances are developed and applied to the case of the given SC (Super Conducting) Maglev line assumed to operate according to the "what-if" scenarios. The models use the inputs compiled from secondary sources implying considering the corresponding results rather illustrative, a basis for further research, and useful for comparing to the available official ones. The SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis based on the results from the application of the models of indicators to the given case is applied for the qualitative evaluation of the potential advantages and disadvantages of the given Maglev line/system compared to the HSR (High-Speed Rail) wheel-rail systems.

Agent-based Simulation of High-speed Maglev Train Operation

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This paper investigates the operational issues of high-speed maglev trains and develops an agent-based simulation model tailored to the characteristics of high-speed maglev systems. The model employs a spatial step-driven simulation approach to achieve high-precision simulation of the high-speed maglev train operation, deriving speed-distance curves. Additionally, a time step-driven model based on a discrete spatial-temporal network is proposed, enabling all train agents to make operational decisions based on the network and accurately representing the temporal connections between trains in multi-train operation simulations. Using a specific high-speed maglev line as a case study, the model's effectiveness is validated. Results indicate that the model can precisely and efficiently simulate multi-train operations and, through train turn-over mode experiments, demonstrate its applicability in addressing high-speed maglev operational issues.

PROTON: A Microscopic Railway Simulation for Large Scale Networks

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The ability to evaluate the robustness of a timetable on a given infrastructure with specific rolling stock in the presence of operational deviations and disturbances is valuable both in long-term (e.g. when planning infrastructure expansions or rolling stock acquisitions) and medium-term planning (e.g. adjusting the timetable for planned restrictions due to repairs). Simulation can help to assess this robustness, but present tools do not work well for simulating large networks, and network effects are difficult to estimate from only local simulations of parts of the network. We present a new microscopic railway simulation model that can simulate large networks (tens of thousands of trains on tens of thousands km infrastructure) in around ten minutes. We discuss the challenges of creating a simulation with a microscopic level of detail for such large networks, both in terms of input data preparation and in terms of computational efficiency. We describe in detail the approach taken at Deutsche Bahn with the model PROTON, which is a Monte Carlo simulation with stochastic modelling of deviations from the timetable (start delays, dwell time deviations, and disturbances) and explicit modelling of train driving characteristics, signaling, and dispatching. We present a case study in which the simulation was able to reproduce the week-by-week changes in punctuality observed over the year 2022. The adoption of PROTON into its planning processes will enable Deutsche Bahn to make better decisions in the future.

Performance results of CBTC on the Copenhagen suburban railways

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The Danish national railway infrastructure operator, Banedanmark, replaced the signals on a 171 km suburban railway network with CBTC (Communications Based Train Control) over a six-year period from 2016 to 2022. A detailed analysis of the public traffic disruption data from 2015 to 2023 finds that the disruptions due to signals have been reduced by approximately 63%. However, the net improvement in punctuality has been hindered by increases in other sources of disruption. The analysis shows no correlation between partial installation of CBTC and reductions in disruption. Only after the entire network was fully implemented was there a reduction in disruption relative to the original technology. The measured effect of the CBTC installation is relatively free from the influence of changes in traffic or other changes in technology. CBTC does appear to shift the source of disruption from track hardware to rolling stock.

Optimizing Slack Time in Public Transport Using a Dynamic Discrete Event Stochastic Simulation Model Accounting for Headway Deviation Effects

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This study focuses on optimizing slack time in public transport timetables using a dynamic discrete event stochastic simulation model, with an emphasis on accounting for headway deviations. Maintaining consistent vehicle headways is challenging due to stochastic variations in running time and dwell time, which often result in increased passenger waiting times and arrival delays. Our model aims to minimize the costs associated with passenger waiting time, arrival delays, end-of-service delays, and slack time, while adjusting the slack time within the timetable. The model specifically incorporates the effects of headway deviation. We explore two slack time distribution strategies: concentrating slack time at layovers and distributing it evenly along the route. The experiment results show that factors such as scheduled headway, boarding times, and the number of stops significantly impact the optimal amount of slack time in both distribution strategies. Optimizing the slack time ratio—slack time scaled by the standard deviation of travel time—proves to be an effective approach for balancing the attractiveness of public transportation with the operational costs of slack time. At the conclusion of this study, the optimized slack time ratio for each combination of variations in scheduled headway, boarding times, the number of stops, and each slack time distribution strategy is presented. Public transport agencies can adopt these optimized slack time ratios for practical implementation in their services.

Validation method for timetable design and simulation tools

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Data quality largely influences the reliability of the output of timetable design and simulation tools. The aim of this paper is to present a validation method for timetable design and simulation tools by using realization data. We discuss the validation of the minimum running times and the conflict detection. In addition, the validation method is applied at NS on a case study in the Netherlands. The results show that it is important to validate tools in order to have realistic results and to avoid unnecessary supplements and buffer in the timetable. Finally, by validating the timetabling tool DONS we show that the minimum running time computation improved in the period between 2018 and 2022.

WED-6-C: Freight Yards

Time: Wednesday, 02/Apr/2025: 2:00pm - 4:00pm · *Location:* POT/251/H
Session Chair: Ivan Belosevic

A Bi-level Routing Method based Multi-Agent Simulation for Evaluating Operational Performance of Railway Marshaling Yards

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This paper presents a comprehensive simulation model designed to accurately describe the operational processes of marshalling yards and to facilitate performance analysis under large-scale train flow scenarios. The complexity of the operations is further compounded by large traffic volumes, which increase the difficulty of identifying spatial and temporal conflicts. By analyzing the yard's functional areas, we developed an topological network and proposed a bi-level routing algorithm to manage the processes and paths of various operations. The model's effectiveness has been validated through real-world application at Wuhan North Marshalling Yard. Experimental results demonstrate that the model is capable of analyzing yard processing throughput performance and operational times under various conditions. This study provides a novel and scalable simulation tool that offers both theoretical innovation and significant practical implications for real-world operations.

Integrated train makeup, hump sequencing, and pullout sequencing in railway marshalling stations

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This paper addresses the integrated problem of train makeup, hump sequencing, and pullout sequencing from a railcar perspective in railway marshalling stations, focusing on assigning railcars from inbound trains to outbound trains, and arranging engines for disassembly and assembly operations. Considering the specific information of railcars, we formulate a 0-1 integer linear programming model to minimize the total railcar dwell time, while satisfying restrictions related to train makeup, disassembly and assembly operations, and other operational and safety requirements. A Biased Random-Key Genetic Algorithm (BRKGA) is developed to solve the problem. The proposed model and algorithm are tested on two sets of instances constructed from a marshalling station in China. Computational results demonstrate that: for small-scale instances with a single hump and pullout engine, the proposed model and algorithm can obtain solutions with a gap of less than 0.5% in a short computation time, which are significantly better than that obtained by a first-in-first-out empirical approach (EA). Furthermore, for large-scale instances with multiple hump and pullout engines, the algorithm emerges as the best approach, since it can obtain higher solution quality within lower computation time when compared with other approaches.

Port-owned transfer train routing and scheduling problem in large sea-rail ports with multiple port zones: An improved adaptive large neighborhood search approach

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Constructing multiple port zones and connecting each with railway lines has become a popular strategy among leading sea-rail container ports globally to handle the surge in container transshipment volumes between rail and maritime systems. To efficiently connect container flows between ports and hinterland rail networks, railway departments have established specific railway container stations (RCSs) beside port areas for sea-rail operations, while port authorities have deployed port-owned transfer trains (POTs) to manage container export and import transportation within the port area. This paper addresses the routing and scheduling problem of POTs. We model this problem as a vehicle routing problem with multiple trips and simultaneous pickup and delivery, incorporating practical constraints such as tasks' time windows and parking capacities at terminals. To efficiently solve the problem, we propose an improved adaptive large neighborhood search (IALNS) heuristic, which has a customized segment-based solution evaluation method to measure time-related attributes and a three-stage feasibility check procedure to ensure feasibility. Meanwhile, our IALNS has several problem-specific operators and enhances standard ALNS by incorporating a backtracking (BT) mechanism to enhance heuristic exploration. Numerical experiments with varying problem settings and data scales verify the effectiveness and efficiency of the proposed methods and obtain managerial insights into the problem. Observations from computational results indicate that the IALNS outperforms CPLEX and ALNS in computational efficiency and solution quality and stability, while greater train carrying capacities contribute to reduced operational costs and improved service punctuality.

Use of Optimised Waiting Probabilities for Dimensioning Track Groups in Rail Freight Stations

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Attractive rail freight transport services require the availability of an efficient infrastructure both on the lines and in the hubs. The quality-oriented and economical dimensioning of track groups in rail freight stations is therefore an essential task of strategic infrastructure planning. The main goal is to determine the required number of tracks and the necessary track characteristics. This paper describes an optimisation model for dimensioning rail freight stations by explicitly considering the track occupancy in a track group and minimising the number of trains waiting in front of the track group. Waiting probabilities can be derived from this, which represent an established decision-making parameter for the dimensioning of track groups.

Optimal Layout Planning Method for Rail-road Intermodal Container Terminals

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As an efficient and eco-friendly mode of freight transportation, growth of road-rail intermodal transportation of containers and trailers is expected to continue in the United States. To effectively meet this increasing traffic demand without sacrificing service or the environmental benefits of multi-modal transportation, estimates of intermodal terminal capacity, performance and emissions are required to inform strategic investments in terminal expansion and equipment utilizing alternative energy sources. To better understand the role of expanding intermodal terminals in a low-carbon and energy efficient transportation system, this work proposes a model to optimize road-rail intermodal terminal layout by minimizing the total travel distances of trucks and terminal equipment given spatial constraints on the parking/stacking area. Since a non-linear model describes the total travel distances and container storage capacity, the Differential Evolution (DE) method is used to solve for the optimal facility layout given a target throughput volume. The resulting parallel terminal layout solutions meet expected storage capacity requirements and specified land area constraints given demand uncertainties. Preliminary results suggest a preference for expanding parking block columns, a fixed number of aisles, a linear increase in total travel distance, and a diminishing marginal effect at key inflection points when the layout shifts from one general configuration to another. The model results can inform strategic investment decisions regarding terminal facility expansions to promote intermodal supply chain sustainability, and also offers insights into identifying and alleviating bottlenecks arising from the intermodal terminal layout and allocated resources at the planning and operations level.

A reward-driven 0-1 integer programming for optimizing railroad flat yard switching: A sequential decision approach

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In this paper, we introduce a novel modeling and solution approach for optimizing switching in railroad flat yards, defined as the Flat Yard Switching Optimization (FYSO) problem. We model the FYSO problem as a network problem where each railcar is represented as a node and each potential shunting action as an arc, forming what we call the Shunting Action Network (SAN). The SAN is formulated as a 0-1 integer programming model that incorporates constraints reflecting the practical requirements of flat yard operations. To enhance this model, we introduce symmetry-breaking constraints tailored to the specific characteristics of the problem. Our approach identifies the necessary shunting activities to rearrange railcars into the desired sequence efficiently. We further develop a sequential decision framework that updates and optimizes the switching process. The effectiveness of our method is demonstrated through its application to an instance from the 2024 RAS problem-solving competition. The proposed SAN model and sequential decision approach align well with the characteristics of the FYSO problem, reducing computational complexity while offering robust performance. This work provides a significant advancement in modeling and solving the FYSO problem, with potential applications extending to different types of rail yards and operational scenarios.

WED-6-D: Rolling Stock and Crew Scheduling

Time: Wednesday, 02/Apr/2025: 2:00pm - 4:00pm · *Location:* POT/361/H
Session Chair: Thomas Schlechte

Rolling Stock assignment Optimization Model using Mixed Integer Programming in Urban Railways

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In this paper, we attempt to optimize rolling stock assignment plans by applying a Mixed Integer Programming (MIP) optimization algorithm to densely operated urban railways in Japan, and we evaluate the efficiency effects on a train timetable. First, we provide an overview of the relationship between tactical train timetable creation methods, tactical rolling stock operation plans, and rolling stock assignment plans in urban railways with multiple depots and complex, dense operations. After that we identify the issues and challenges of current methods. Next, we introduce an algorithm using MIP tailored for rolling stock assignment planning in urban railways. Following this, as a case study, we apply the proposed method to the actual rolling stock assignment plan of Odakyu Electric Railway to verify its effectiveness. We also evaluate the efficiency improvements on the train timetables when the rolling stock assignment method is changed and show the results.

A deep reinforcement learning approach for integrated optimization of train scheduling and rolling stock circulation planning

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This study proposes an optimization method for train scheduling and rolling stock circulation planning based on a deep reinforcement learning framework within a hybrid action space to address real-time passenger demand. The optimization problem is formulated as a Markov decision process involving simultaneous discrete and continuous action spaces, with the objectives of minimizing passenger waiting time and reducing operator costs by optimizing scheduling and rolling stock circulation planning. To address computational challenges, the solution is computed using a hybrid proximal policy optimization approach designed for hybrid action spaces, with constraints managed through mask operations. The method is validated using the Beijing Metro Changping Line as a case study. The experimental results demonstrate that the advantages of the proposed method over the heuristic method in terms of computation time and solution results.

A Hybrid Heuristic Solution Approach to the Rolling Stock Rotation Problem with Maintenance

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Assigning suitable railway rolling stock vehicle compositions to trips of a given timetable is a basic problem of every railway operation; it has been well investigated in the literature in a broad variety of different settings. In this paper a variant is studied that includes distance based maintenance constraints for the operated rolling stock types. We present a heuristic solution approach where first a relaxation of the original problem is solved via a column generation procedure. During this procedure maintenance feasible paths for the operated vehicle types are generated on the fly which are used later on in a second path based integer programming formulation to compute solutions for the original problem. The presented solution approach is evaluated on real world instances for long distance railway passenger transport. The computed solutions are compared to solutions found with the approaches of Borndoerfer et al. (2016) and Grimm et al. (2023).

Short-Term Crew Rescheduling: Extending the Scheduling Options in a Tabu-Search-Based Approach

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We consider short-term crew rescheduling for a one-day schedule. We assume that several drivers take leave before the operating schedule due to sickness or other reasons, while there is a limited number of standby drivers available at different depots. The tasks of the absent drivers need to be reassigned. Overall, we aim to minimize the number of unassigned tasks, while even the number of drivers who work overtime, the total overtime, and the average travel time per taxi trip are integrated into the objective. Due to the complexity of exact methods, we use heuristic approaches to solve this problem. In this paper, we present our modified tabu-search-based approach for crew rescheduling by broadening neighborhood solutions and allowing several relaxations to avoid canceling trips. We evaluate our method on real-world data for the Mälartåg regional-train system in Sweden. We investigate the effects of different relaxations and we compare the impact based on the number of unassigned tasks and the objective value.

Integrated optimization of train formation plan and rolling stock scheduling in high-speed railway network

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Efficient matching of passenger demand with rolling stock units has always been a significant focus in high-speed railway planning. However, the existing sequential planning process severely limits the improvement of rolling stock utilization efficiency. Addressing the time-varying characteristics and uneven spatiotemporal distribution of high-speed railway passenger demand, this paper proposes an integrated optimization model for train formation plan and rolling stock scheduling. Comprehensively considering the circulation rules, maintenance requirements, deadhead movements, and coupling and decoupling operations of rolling stock units, the model aims to minimize the number of rolling stock units, the number of coupling and decoupling operations, deadhead mileage, and maintenance times. The performance of the proposed model is analyzed using the Beijing-Tianjin-Qinhuangdao high-speed railway as a case study. The results demonstrate that, on the basis of satisfying passenger demand, the integrated optimization of train formation planning and rolling stock scheduling can effectively reduce the number of rolling stock units, decrease operating costs, and enhance rolling stock utilization efficiency.

An integrated optimization model for the timetable and train unit circulation plan with short-turning and flexible train formation strategies in metro systems

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In metro systems, the timetable scheduling problem consistently aims to improve passenger service quality while reducing operational costs. To this end, the present study presents an integer programming (IP) model for the integrated optimization of train timetable planning (TTP), train formation planning (TFP), and train unit circulation planning (TUCP) to address the tactic decision-making problem of train formations and routing schemes applied to both short and full routes. In particular, the model incorporates the dynamic use of siding tracks within the TUCP problem and the collaborative optimization of routing and formation schemes. An adaptive large neighborhood search (ALNS) algorithm is prompt, featuring five destruction operators that alter service frequency, route, interval/train headway, train unit types, and train formation type, along with three corresponding repair operators to restore connections, timetables, and storage capacity. A real-world case study based on Line 5 of Chongqing Rail Transit is used to validate the effectiveness of the proposed model and algorithm. An analysis with different weights for the two objectives shows that a greater weight on the services' quality leads to denser train operations and a higher proportion of trains operating with long formations and full-route services.

WED-8-A: Timetabling and Scheduling 2

Time: Wednesday, 02/Apr/2025: 4:30pm - 6:30pm · *Location:* POT/051/H
Session Chair: Pieter Vansteenwegen

A Multi-Commodity Flow Heuristic for Integrated Periodic Timetabling for Railway Construction Sites

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Rescheduling a railway system comprises many aspects, such as line planning, timetabling, track allocation, and vehicle scheduling. For periodic timetables, these features can be integrated into a single mixed-integer program extending the Periodic Event Scheduling Problem (PESP) with a routing component. We develop a multi-commodity-flow-based heuristic that allows to compute better solutions faster than a black-box MIP approach on real construction site scenarios on the S-Bahn Berlin network.

A Review and Road Map of (Interactive) Multi-Objective Optimization in Railway Timetabling and Rescheduling

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Timetabling and rescheduling are essential components of railway systems. Under the pressure of increasing demand for railway networks, academia has worked these last decades on the modeling and solving of these tasks. As these problems are NP-hard, achieving reasonable computational time and scalability remains challenging. To be truthful to reality, models must consider the interests of the involved stakeholders. Satisfying these different preferences leads to conflicting objectives which multi-objective methods can solve. However, solving these problems with single-objective optimization is still the standard, even though railway timetabling and rescheduling are fundamentally multi-objective problems. To our knowledge, this work presents the first literature review on multi-objective optimization in railway timetabling and rescheduling. Weighted sum, \(\varepsilon\)-constraint, and evolutionary methods are the most used methods. This study identifies several literature gaps, for instance, the lack of studies using multi-objective methods other than the three mentioned, the lack of models with more than three objectives, and the absence of interactive multi-objective methods. Finally, interactive multi-objective optimization is presented as a promising research direction. This approach addresses the challenges of computational cost and user acceptance. A road map for its implementation is presented and design possibilities and challenges are discussed.

A Space-time Network-based Approach to Add Comprehensive Inspection Train to the Existing Schedule

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This study introduces a space-time network-based approach for incorporating Comprehensive Inspection Trains (CIT) into existing railway schedules, addressing the dual objectives of enhancing inspection efficiency and minimizing operational disruptions. Firstly, the constraints that need to be considered when adding train line for CIT are comprehensively analysed and modelled, and a mixed-integer nonlinear model with the objective of minimising the total number of stops is constructed. In order to eliminate the difficulty of solving this model, based on the original space-time network method, more kinds of train event arcs are introduced to accurately portray the train operation process, especially the extra time consumed due to the acceleration and deceleration process is also reflected in the network construction process. The feasibility of various event arcs is evaluated with time windows, and the original problem finally transforms into the equivalent shortest path problem on a feasible event arc network. The processing procedure includes key stages such as station space-time discretization, interval operation event processing, station capacity handling, and network simplification. Experimental results indicate that the approach effectively resolves all station capacity conflicts, compresses inspection durations, and optimizes the number of stops. Remarkably, the number of non-full-speed inspection sections is reduced by 43.16%, demonstrating the model's efficiency. Additionally, the computational demands of the proposed solution process are manageable, ensuring the practical applicability of this method in railway operation planning.

Integrated optimization of train platforming and rolling stock scheduling for periodic timetables

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The rapid expansion of high-speed railways and escalating passenger volume in China have posed new challenges for railway operators in terms of efficiently utilizing the complex system of transportation resources to meet passenger demand. Both the Rolling Stock Problem (RSP) and the Train Platforming Problem (TPP) are crucial tasks in the railway operation plan and are often handled separately in a sequential manner in daily operation. By optimizing an integrated problem, better coordination can be achieved between the rolling stock schedule and the track utilization plan. To address rolling stock scheduling and train platforming within periodic timetables of one-day period, this paper proposes an integrating space-time-state network-based multi-commodity network flow model with safety constraints, track capacity constraints, and (de)coupling constraints. Two dual decomposition approaches are introduced to efficiently solve the model, i.e., the Lagrangian Relaxation (LR) based heuristic approach and the Alternating Direction Method of Multipliers (ADMM) approach. The proposed model and approaches are validated through the real-world Shandong high-speed railway network instances. Two feasible rolling stock schedules with corresponding platform utilization plans are acquired within acceptable computation time, and ADMM outperforms in both solution efficiency and quality.

Robustness Measures for Stochastic Parallel Machine Scheduling and Train Unit Shunting

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In this paper, we investigate measures that can give us information about the robustness for complex scheduling problems. We identify 14 robustness measures from the literature, as well as introduce 4 new ones. We then use simulation to investigate how well these robustness measures correlate with the stability of the objective function under disturbances (quality robustness), and with the stability of the schedule itself (solution robustness). We first do this in the context of Parallel Machine Scheduling, which is a very general setting that is comparable to many practical situations. We then take the results from that investigation and use the best performing measures as objectives in a local search for the Train Unit Shunting Problem with Service Scheduling. We investigate which of these measures give us a better quality robustness, and which measures give us a better solution robustness. We look at how these measures perform under different ways of inserting slacks into the schedule. We show how the performance of the measures can differ in these different cases, and conclude with what we believe to be a good set of robustness measures to consider for any scheduling problem.

Investigating Departure Time Flexibility in Urban Rail: The Impact of Travel Time, Departure Hours, and Trip Type

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Urban rail networks play a pivotal role in modern metropolitan transportation systems, facilitating millions of daily commutes while reducing traffic congestion and promoting environmental sustainability. However, these networks face challenges such as peak hour overcrowding and underutilization during off-peak periods. This study introduces a framework for quantifying departure time flexibility among metro rail commuters using smartcard data. Traditional approaches for assessing commuter behavior rely on manually collected data, which is resource-intensive and prone to inaccuracies. In contrast, this study employs a mixture distribution model, combining beta and uniform distributions, to analyze commuters' flexibility dynamically. The model assumes two commuter groups: those adhering to fixed schedules, represented by a beta distribution, and those arriving randomly, represented by a uniform distribution. Parameters of the mixture model are functions of travel time, departure time, and trip type, allowing for flexibility comparisons based on commuters' contextual factors. Results indicate that travel time negatively impacts the proportion of randomly arriving passengers, while non-peak departures are associated with higher flexibility levels. Transfer trips also contribute to flexibility but to a lesser extent. This methodology enables transit planners to evaluate flexibility patterns at different times and locations, supporting strategies such as dynamic pricing to manage peak demand. By leveraging large-scale transit data, this framework provides a more accurate, adaptable approach to understanding and enhancing commuter flexibility across metro systems, offering practical insights for demand management and policy design.

WED-8-B: Rail Operations, Infrastructure, and Safety

Time: Wednesday, 02/Apr/2025: 4:30pm - 6:30pm · *Location:* POT/151/H
Session Chair: Alex Landex

Empirical Analysis of Longer Train Derailment Rates and Causes

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This study presents an empirical analysis of the relationship between freight train length and derailment rates on major (United States ClassI) railroads using data from the period 2018 to 2023. By combining detailed traffic exposure data from the Association of American Railroads (AAR) with derailment records from the Federal Railroad Administration (FRA), it addresses a critical gap in understanding the possible effect of train length on derailment rates. The analysis focuses on three key aspects: overall derailment rates, derailment causes, and different types of freight train. Although the findings suggest a statistically significant correlation between train length and derailment rates, particularly with trains more than 150 cars the results are more nuanced. Long train derailments rates initially increased but in the past several years have declined nearly back to their initial rates. Furthermore, only some railroads displayed this pattern of increase and decline, while the rates for others remained static throughout the study period. Train handling and brake operation are identified as the primary factors contributing to the elevated derailment rates in longer trains. Derailments due to these causes increased from 2018 to 2021 but declined in 2022, 2023, and 2024. When these two causes are excluded, the derailment rate for trains longer than 150 cars decreases by an average of 35%, and the relationship between train length and derailment rates became statistically insignificant. Additionally, the study compares derailment rates across unit, manifest, and intermodal trains, revealing that manifest trains generally have higher derailment rates. This analysis offers unique insights into the safety challenges associated with long-train operation and emphasizes the need for targeted risk management strategies. It emphasizes the need for further research on developing a quantitative model that considers train length, train type, derailment causes, and operational factors to help balance the benefits and risks of longer trains.

Redesigning Early Notice Discount Incentives for Rail Maintenance Planning

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In GB rail, regulators are faced with the challenge of designing incentives such that the managers of the infrastructure provide sufficient notice prior to the maintenance work being performed. The purpose of this is to ensure that both the customers and the operating companies have adequate time to make alternative arrangements around these planned disruptive periods. The current legislation, known as Schedule 4 of the Track Access Contract, awards an early notice discount on the amount of compensation owed to the operator by the infrastructure manager, for any possessions notified more than 22 weeks prior to the scheduled date. This policy has received criticism, however, for failing to provide any incentive to notify operating companies early after this 22-week threshold has been passed. We also argue that it sometimes places pressure on the infrastructure managers to schedule works before plans are completely finalised, causing late notice changes, unplanned disruption and cost inefficiencies. In this paper we analyse the consequences of this incentive policy using prospect theory; namely, how the fundamental nature of stepwise discounts create this pressure to accept the discount at its time threshold, even when it may not be sensible to do so. We also propose an alternative incentive policy, utilising a continuous discount function, that aims to provide an incentive to notify early even when the 22-week threshold has passed, while also removing the pressure to make a decision immediately at the discount threshold. Using a linear approximation of the compensation function, we demonstrate how certain levels of discount under this proposed scheme may be used to influence behaviour.

An Intermittent Partial Electrification Network Design Problem for the Introduction of Battery-Electric Regional Trains

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Regional non-electrified railway networks require replacement of diesel traction to meet increasingly stringent emission reduction targets. Since full electrification of these networks is often not economically viable due to their low utilization, battery-electric multiple units (BEMUs) are recognized as a potentially suitable long-term solution, offering zero-emission trains operation while requiring only partial tracks electrification. One of the main challenges when introducing BEMUs is determining an optimal electrification layout, i.e. the location and the length of electrified track sections while taking into account the vehicles' and infrastructure technical characteristics and constraints alongside the requirements related to maintaining current timetable and quality of service. Present research formulates this as an intermittent partial electrification network design problem and develops an optimization framework that integrates high-fidelity BEMU simulation model in deriving a cost-optimized network electrification configuration. The proposed method is demonstrated using the existing non-electrified regional railway network in the Netherlands with the rolling stock and transport services of Arriva as a case. The obtained solution provides about 30% lower capital costs compared to the conventional continuous partial electrification approach, and about 3.5 times cut in these costs compared to the fully electrified network. Additionally, further costs reduction is observed by increasing the maximum current absorption limits at standstill and by introducing flexibility in terms of operational margins.

Implementing Measures for Timetable Robustness in Presence of Regulatory Constraints

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Over 128 thousand trains have arrived in the Frankfurt Main Station between 1st of January and 31st of August 2024 with an average delay of 9 minutes. Every third train was officially above the Deutsche Bahn punctuality threshold, thus not running according to its allotted capacity spot.

The timetable needs to be stabilized; thus, the important question arises on the "How?". This is particularly relevant in the context of the current railway regulatory framework in Germany.

The goal of this industrial paper is to introduce the adaptions in timetabling policy planned for the annual timetable 2026, focusing on the implementation of the symmetric buffer times in the timetable construction, to limit delay propagation. Furthermore, the paper gives the framework in which the policy adaption happened.

Train-to-yard assignment problem in a railway bidirectional marshalling station

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In this paper, we deal with the train-to-yard assignment problem at bidirectional marshalling stations, which lies on flexibly assigning inbound/outbound trains to receiving/departure sub-yards. By this way, the connection between inbound trains and outbound trains can be enhanced, and the operational efficiency in marshalling stations can be increased. This problem is formulated as a mixed integer linear programming model with the objective of minimizing the total railcar dwell time, while assembly requirements, capacity limitations, and other operational and safety constraints are taken into account. Considering the fact that practical operation plans are scheduled on the basis of the gradually updated information and situation, a rolling horizon algorithm is developed to solve large-scale instances efficiently. Computational results on a set of different-scale instances (derived from Zhengzhoubei Station) demonstrate that our original model performs well when solving small-scale instances, and our algorithm computes (near-)optimal solutions for all tested instances within an acceptable computation time. Besides, sensitivity analysis on different receiving and departure conditions has proved the scalability of our algorithm.

Passenger-Oriented Train Routing and Stop Planning within Railway Hubs

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As the number of passenger stations in large-scale railway hubs increases, traditional experience-based assignment of trains to stations struggle to meet the complex travel demands of passengers. This paper proposes a passenger-oriented Train Routing and Stop Planning optimization model to address these challenges. The model minimizes both intra-city travel costs for passengers and train operating costs while respecting constraints such as train seating capacity and station and line capacities. It also accounts for the limitations on the adjustment of train routes and stop plans to ensure practical feasibility. Applied to a real case study of the Beijing Railway Hub in China, the results show significant savings in passenger travel costs, thereby validating the model's effectiveness.

WED-8-C: Freight Yards and Freight Flow Optimization

Time: Wednesday, 02/Apr/2025: 4:30pm - 6:30pm · *Location:* POT/251/H
Session Chair: Tyler Dick

Determining the Capacity of Single-Track Heavy-Haul Railway Lines under Train Group Operation Based on Minimum Cycle Time of Restriction Section

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To address the issue of capacity limitations of single-track heavy-haul railways, train group operation is implemented to enhance railway capacity at the level of transport organization. In this paper, the basic concept and operation principle of train group operation is introduced. Based on the single-track cyclical timetable, the component of timetable cycle time is analyzed, and an integer linear programming model is proposed to calculate the minimum cycle time of the restriction section by optimizing train meet-pass plan and the arrangement of operation time at each station. In accordance with the operation characteristics under train group operation, the calculations of each parameter in the model are calibrated, and the theoretical capacity of single-track heavy-haul railway lines is then calculated. To examine the model, a real single-track heavy-haul railway line in China is selected as a case study. The results show that the train group operation can significantly enhance the capacity of single-track heavy-haul railway lines under different train group strategies, but the capacity improvement effect presents a fluctuating state with the number of trains in a group increasing. For railway operators, the optimal capacity needs to be determined concretely considering the line condition and operation organization. This method provides an evaluation of capacity under train group operation, offering valuable guidance for the operation and subsequent planning of single-track heavy-haul railways.

Real-time Optimization of Transport Chains for Single Wagon Load Railway Transport

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The freight branch of the Swiss national railways, SBB Cargo, offers customers to ship single or few wagons within its wagon load transportation system (WLV). In this system, wagons travel along a transport chain which is a sequence of consecutive trains. Recently, SBB Cargo redesigned its IT systems and renewed the computation of these transport chains. This paper describes the main design decisions and technical details: data structures, search algorithms, mathematical optimization of throughput in the real-time setting, and some selected details for making the algorithms work in the operational software. We also comment on the employed technology stack and finally demonstrate some performance metrics from running operations.

Tactical level rail freight crew planning: A case study on Indian Railways network

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This paper addresses tactical level crew planning for freight rail operation. We propose a robust policy for the crew capacity required at a crew base considering the uncertainties related to the number of freight services being operated on a day and their traversal times. Crew duties to operate a set of freight services are generated constructively using a discrete event simulation approach by incorporating the rules and guidelines related to crew allocation. We determine the crew capacity required at a crew base as a factor of the number of freight trains being interchanged there over a day. For the test case of Bhusaval (BSL) division (Central Railway, Indian Railways), the required crew capacity is found to be 1.2 times the number of trains interchanged at the crew bases over a day. As per this policy, the overall crew capacity required in BSL division is found to be 14% less than the current crew capacity.

Railcar Flow Estimation Model Based on a Two-Layer Time-Space Network

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In railway freight transport, accurate estimation of railcar flows is crucial for enhancing the planning quality of daily railway operation and for making adjustments to railcar flows. It serves as a key prerequisite for ensuring stable operation and reasonable flow distribution of network railcars. However, the lack of precise railcar flow estimations can lead to large number of railcars backlogged in stations. To address this challenge, we first depict the operational process of railcar flows based on a time-space network. Subsequently, to minimize the in-transit operating costs of railcar flows during the estimation period, we construct a mixed-integer programming model. This model can predict the distribution state of railcar flows in future periods. Finally, the computational results show that the model can find high-quality solutions within a reasonable computation time. It can accurately depict the operational characteristics and operational requirements of railcar flows. This method contributes to railcar flow organization and improves the performance of freight transport.

A planning framework for high automation of rail cargo order processing

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The cargo market is highly dynamic and cost driven. In order to compete on this market with other means of cargo transportation, railway undertakings require software solutions which can provide rail cargo customers reliable transport plans for any given order of cargo transport in a short amount of time. SBB Cargo has introduced DXC Technology's Rail Cargo Management Solution during the last 4 years. The solution's order planning functionality has been widely extended to provide best possible support for the planners through a high degree of automation. The system is applied for all kinds of traffic, allows manual interaction at all planning stages and – as an end-to-end solution from order to cash – allows full customer focus at any time. The paper describes in detail the collaboration between cargo undertaking and infrastructure manager, the systems developed to support the train path planning process and the order planning processes for different kinds of traffic.

WED-8-D: Capacity and Quality

Time: Wednesday, 02/Apr/2025: 4:30pm - 6:30pm · *Location:* POT/361/H
Session Chair: John Preston

A Uniform Assessment Standard for Evaluating the Operational Quality of Railway Lines

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Performance analyses are an essential basis for the development and evaluation of railway infrastructure. Analytical and simulative methods are mainly used for this purpose. In analytics, the extent of unscheduled waiting times is used to assess the operational quality of railway lines, while simulations evaluate operational quality based on the change in delays between two locations. In Germany, the respective quality standards can be found in Guideline 405 of DB InfraGO AG, Germany's state-owned railway infrastructure manager. However, the current evaluation methods in analytics and simulation are not harmonised, resulting in the inability to guarantee comparable results regardless of the applied method. For the dimensioning of railway lines consistent results are essential. Therefore, the aim of this paper is to develop a new assessment standard that enables uniform results about the operational quality of a railway line through the use of both analytical and simulative methods. In the first step, the current quality standards of analytics and simulation are briefly described, and the differences between the two methods are highlighted. An evaluation strategy for the new assessment standard is then developed and described in detail. Furthermore, an example is used to illustrate the finished process of the methodology. Finally, the results of the new assessment standard are validated using generic railway lines.

Collaborative capacity analysis of urban rail transit lines with mixed turnaround operations on multiple stations

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The capacity of the urban rail system gradually comes to the designed limit with the rapid development of the economy and the increasing demand. Thus, it is necessary to accurately assess the capacity of urban rail transit lines during their design, operation, upgrading, and reconstruction phases. The overall capacity of a rail transit line is mainly affected by the operations at the bottleneck. However, the operational collaboration of the trains in various parts (i.e., stations and segments) of the transit line might also impact capacity performance significantly, which the existing research usually neglects. In this paper, we calculate the urban rail transit capacity considering the turnaround operations in multiple stations based on the UIC 406-like timetable compression method. Specifically, we propose a MILP model for compressing a given rail transit line timetable, considering the microscopic turnaround operations of multiple stations. To describe the turnaround operation in detail, we introduce a microscopic facility model for the stations with complex layouts. Therefore, the different turnaround procedures (i.e., the station-front and beyond-station turnaround) can be described. We take Line 18 of the Guangzhou Metro as an example to conduct experiments. The result shows the influence of various factors (e.g., the minimum departure headway, turnaround operation mode, the full-part routes, and the even of departure headway) on the overall capacity, which can help find the bottleneck of a timetable and put forward the possible enhancement measurements of capacity.

Service Frequency Variability and Its Dependence on the Passenger Number and Fleet Composition

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Rail and metro systems are generally considered uncongested, as variations in running times between stations are negligible compared to other systems, such as road transport, where congestion can increase travel times more than three times compared to normal conditions. This study analyses the effects of variability in the number of passengers on rail and metro convoys (and related variation in total convoy weight) on running times. Indeed, although the variations in running times are neglectable, they can compromise the stability of service frequency, triggering mechanisms that lead to a deterioration of system performance. Therefore, the paper proposes a methodology for analysis to assess whether such variability could influence the stability of service frequency. An application to Line 1 of Naples metro systems, in Italy, has shown that in ordinary conditions the layover time is able to absorb any running time variations thus ensuring the stability of the service frequency.

The Impact of Freight Trains on Passenger Train Punctuality : A Case Study

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This paper analyses the effects of freight train movements on the punctuality of passenger trains on a double-track line with mixed traffic in Sweden. A specific focus is placed on the timetable deviations experienced by passenger trains when overtaking slower freight trains. The methodology developed allows for measuring time deviations around these interactions. A case study was conducted using data from 2022 for the highly utilized Southern Mainline. The results show that freight trains running ahead of schedule generally cause less delay to passenger trains, and that late-running passenger trains are less affected by overtaking events compared to those running on time. The findings contribute to a deeper understanding of mixed-traffic rail operations and their impact on passenger train punctuality

How much is enough? A comparative Analysis of Delay and Recovery Time in Railways for Switzerland, Austria and Germany

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Significant differences in railway performance, measured by delays and especially as punctuality levels can be observed between different European countries. A strategy to improve the performance in countries with relatively poor quality levels is to compare against better performing peers while trying to understand reasons for differences, and finally to derive paths for possible improvements. We therefore comparatively analyze delays using publicly available data only. First, we analyze whether delays in the terminus stations of trains are a function of the lengths of their train runs. Second, we investigate to what extent delays are absorbed between two consecutive stops, in function of the running time between these stops. Last, we empirically approximate the amount of recovery time, or, running and dwell time supplement, that is included in the timetable, and compare this to the empirically observed degree of absorbing delays. It will turn out that all countries apply larger recovery times than the 7% of pure running and dwell time recommended in the UIC code 457-1. Nevertheless, recovery times in one country are considerably larger than in others. The country also shows significantly higher absorption of delays and greater overall punctuality: Switzerland. The Swiss national operator SBB applies a recovery time of 10.6% on average and also for long sections. The results shows that even an operator with reliable infrastructure and rolling stock needs to apply relatively high recovery times in order to reach high punctuality.

A Queueing-Based Approach for Timetable-Independent Railway Station Performance Analysis

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Railway stations serve as critical nodes within railway networks, facilitating connections across diverse travel directions. Traditionally, the analytical performance analysis of railway stations has been divided into two distinct components: the examination of stopping tracks and the evaluation of route nodes, the locations within a station where switches determine the direction of travel. This study introduces an innovative Continuous-Time Markov Chain model that represents a comprehensive queueing system encompassing the entire railway station. By deriving timetable-independent performance indicators, this model provides a robust framework for assessing station performance. Consequently, it equips infrastructure operators with a holistic tool for infrastructure planning and evaluation.

THU-1-A: Timetabling and Scheduling 3

Time: Thursday, 03/Apr/2025: 9:00am - 11:00am · *Location:* POT/051/H
Session Chair: Giorgio Medeossi

Enhancing Railway Operation Efficiency and Capacity with Virtual Coupling: Simulation-Based Comparative Analysis with CTCS-3 System

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In railway transportation, train headways are crucial determinants of the density and operational efficiency of high-speed railway lines, and they serve as key limiting factors of line capacity. This paper explores the use of Virtual Coupling (VC) control system to reduce train headways, examining specific strategies and potential capacity improvements for enhancing overall railway transportation. To thoroughly evaluate the practical application of VC system, the study extends from local optimization of individual station operating scenarios to a comprehensive analysis of train operations. It takes into account multiple spatial and temporal factors, including station signal conversion technology, coupling and decoupling strategies, and operational speed within synergistic optimization settings. The findings demonstrate that train operation efficiency can be maximized while ensuring safety through the appropriate setting of key operational parameters. Numerical experiments using real data from a high-speed railway station in China reveal that train headways can be shortened by 26%-48% in a VC individual station operating scenario. For the entire train operation process, the time required for trains to continuously enter the station parking area under VC system is reduced by 20%. In scenarios where two trains transition from “departure-through” to “through-arrival”, the initial separation distance required for the two trains is shortened by at least 50%, and the deceleration period for the following train is reduced by 46%, even surpassing the performance of trains operating continuously at ultra-high speeds.

Unveiling Connectivity Patterns of Railway Timetables through Complex Network Theory and Infomap Clustering

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This paper presents a novel approach to analysing railway timetable connectivity using complex network theory and the Infomap clustering algorithm. By transforming railway timetables into network representations, we examine the connectivity and efficiency of the Norwegian railway system for the timetables of the current 2024 year and for a future timetable of year 2033. We define and apply the Timetable Connectivity Index (TC), a comprehensive measure that evaluates the overall connectivity based on the number of services, travel times, and the hierarchical structure of the network. The analysis is conducted across three distinct network spaces: Stops, Stations, and Changes, with both unweighted and weighted networks. Our results reveal key insights into how infrastructural developments, service frequencies, and travel time adjustments influence network connectivity. The findings provide valuable insights for railway planners and operators, aiming to improve the efficiency and reliability of train networks.

Improving Punctuality by Optimizing Supplement Allocation in Regular Interval Timetables

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Railway delays disrupt operations, impacting network quality and efficiency. Timetable supplements, providing time reserves, are vital for delay recovery but can also reduce attractiveness and capacity. Our approach uses a heuristic algorithm to automatically optimize supplement placement for individual trains, improving punctuality substantially. In this paper, we continue and improve prior research by applying the methodology to train families in a regular interval timetable. Though optimizing trains individually in eg peak hours is no longer possible, we show that still a significant albeit smaller increase in timetable punctuality is possible.

Air-Rail Timetable Synchronization with Itinerary-Based Passenger Flow

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The integration of rail and air services has been attracting increasing attention with the growing emphasis on multimodal transport systems. In this paper, we propose a passenger-centric Air-Rail Timetable Synchronization (ARTS) model to improve the passenger transfer experience in integrated air-rail transport networks. The model applies a time shift strategy to existing rail and air timetables to provide more connections and smoother transfers for multimodal travelers. It also captures the passenger itinerary shifts resulting from timetable adjustments. The ARTS model considers three key objectives—unserved demand, transfer time, and timetable deviation—to balance synchronization performance with operational impacts. The problem is formulated as a multi-objective mixed-integer linear program. The effectiveness of the proposed method is demonstrated through a real-world case study of the Spanish rail and air network. The results show that the ARTS model can significantly reduce passenger transfer times. The results also reveal that considering passenger itinerary shifts in the ARTS problem represents a more realistic system and leads to a more efficient synchronized timetable.

Multi-stage game-theoretical model for multi-modal railway network considering asymmetric competition and cooperation relationships

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The advancement of autonomous regional railways has led to the emergence of numerous operators, creating a competitive-cooperative market landscape. The market position of these operators is often asymmetric, leading to unequal decision-making order, where the first movers may even limit the development of other operators by setting low ticket prices and high transport capacity. However, in most previous studies about competition-cooperation research in transportation systems, the asymmetric competition-cooperation relationships among different railway operators have not been considered. Therefore, this paper introduces a multi-stage game-theoretical model based on Nash equilibrium, where the asymmetry of the market position and decision-making sequence for different railway operators are captured. It incorporates the simulation-based passenger assignment model as its lower-level programming; its upper level is a decision-making model to obtain a Nash equilibrium solution among various railway operators. Considering the decision-making priority of some railway operators, the decisions made by these operators are sequential. To obtain the Nash equilibrium solutions in an acceptable computing time, a customized dynamic searching procedure (DSP) is developed for the proposed multi-stage game-theoretical model. Moreover, the designed approximate timetabling algorithm and multi-agent-based simulation algorithm are combined to update the passenger assignment results and evaluation indicators in the searching process of the designed DSP method. Our results indicate that the proposed method can account for the asymmetric competition-cooperation relationships among different railway operators. High-priority operators tend to improve the service frequency of the lines managed by multiple corridors or multiple operators in the cooperation strategy, to decrease the operation cost and save the travel cost for passengers.

High-Speed Railway Timetable Optimization Algorithm Based on Deep Reinforcement Learning

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The timetable is a fundamental technical document in high-speed railway operation. The optimization of timetables involves numerous factors and is a classic problem in railway transportation organization, essentially a complex combinatorial optimization problem. The Deep Reinforcement Learning method combines the feature extraction capabilities of deep learning with the "trial and error" learning paradigm of reinforcement learning, providing a new approach to intelligent timetable optimization. This study integrates deep reinforcement learning with the characteristics of high-speed railway timetables, modeling the train orders in sections optimization problem as a Markov decision process. It proposes a train orders in sections optimization method based on the Double Deep Q-learning Network model, supplemented by a fixed-order train timetable optimization model aimed at minimizing the occupancy of train section capacity while considering various operational constraints. The proposed models are tested using the actual operational timetable optimization case of the Beijing-Shanghai high-speed railway. The results demonstrate that the optimized train timetable obtained through the application of deep reinforcement learning performs well, indicating that the high-speed railway timetable optimization method based on deep reinforcement learning has significant practical value.

THU-1-B: Rescheduling and Traffic Management 2

Time: Thursday, 03/Apr/2025: 9:00am - 11:00am · *Location:* POT/151/H
Session Chair: Joaquin Rodriguez

A MaxSAT Model for Solving the Track Maintenance Possession Problem for the Railway Network in Germany

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We study the Track Maintenance Possession Problem which schedules maintenance works on railway tracks so that the maintenance machines are efficiently assigned and traffic restrictions are not violated. In this particular version of the problem, the maintenance works should be assigned to predefined time slots, so-called containers. We are provided real-world data for the maintenance demands, the containers, the available machines and the traffic restrictions for the whole railway network in Germany for one year. We present a Mixed Integer Program formulation for the problem and give a mathematical proof that it is NP-hard to solve. In order to be able to solve the problem on the large instance size nonetheless, we propose a Maximum Satisfiability encoding and solve the problem with a state-of-the-art solver. In our result, 95% of the maintenance demands are fulfilled which is close to an upper bound we can provide.

Simultaneous scheduling and arrival time prediction of freight trains on shared passenger-freight railway corridors

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Detailed planning of railway operations is commonly considered as important for efficient and punctual operations. Despite this, freight trains often deviate considerably from the schedule, which impose challenges for receiving yards and freight customers. To mitigate this, two related problems can be formulated, namely, to reschedule freight trains as soon as a predicted departure time can be obtained, and to predict arrival times at receiving yards and other important nodes. However, these problems cannot be fully separated since the timetable is critical for the predicted arrival times. For this reason, we extend a method that combines machine learning and simulation for arrival time prediction by integrating it with a combined simulation-optimization approach for robust timetabling to address the joint scheduling and arrival time prediction problem. The proposed method is evaluated in a simulation study on the Swedish Western Main Line. To derive insights on the method's performance and potential improvements, four variants of the method, as well as a state-of-the-art ML-assisted macro simulation-based method for predicting arrival times, are compared. In simulation, the new method demonstrates superior performance, in terms of arrival time predictability, compared with the state-of-the-art method for arrival time prediction; the mean absolute deviation with respect to scheduled arrival times was reduced from 33.6 minutes to between 4.2 and 6.1 minutes, whereas the mean absolute prediction error was reduced between 29% and 40%. Hence, combining scheduling and arrival time predictions improves both punctuality and predictability of freight operations.

A New Approach for Rerouting Multiple Trains During Construction Works and Major Disturbances

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The rerouting aspect of railway rescheduling has received little attention in research. Train rerouting occurs frequently when maintenance works have to be planned, but also during large disruptions. We develop a new heuristic approach based on solving independent set problems, and compare it with simpler, greedy approaches. We assume that some part of the railway network is fully blocked and that the infrastructure manager provides a set of trains that has to be reinserted to the timetable. Our algorithm first selects a set of candidate paths for each affected train, and then obtains a minimum cost solution out of these candidate paths by solving a weighted independent set problem. We include a case study of a closure of the Swedish southern main line, where the alternative route consists almost completely of double-track segments. We also elaborate on extensions of the algorithm for an improved handling of overtakings.

Impact of Track Discretisation on Conflict Detection and Resolution under ETCS with Onboard Train Integrity Monitoring

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To further improve the capacity on the European railway network, next-generation distance-to-go signalling systems are being developed in the context of the European Train Control System (ETCS). This paper investigates the impact of track discretisation granularity on conflict detection and resolution for ETCS with onboard train integrity monitoring. The study enhances a previously developed model for fixed-block distance-to-go signalling introducing a track discretisation procedure and reformulating safe train separation constraints at switches. The assessment is performed on a junction and a corridor case study, using track discretisations with maximum section lengths from 50 to 800 metres. Though finer discretisations potentially improve the model objective, computation times quickly increase. While the results show minimum effects of the track discretisation on the conflict detection and resolution, they suggest that maximum section lengths of 200 or 400 metres may offer a good balance between solution quality and computation complexity, depending on the track layout and traffic density.

A Constraint Programming Approach to Coordinated Train Rerouting and Rescheduling in Railway Traffic Management

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Railway traffic controllers often are faced with the challenge of trains deviating from their scheduled timetables due to unforeseen disruptions, such as technical failures. This paper presents a coordinated approach to train rerouting and rescheduling that aims to mitigate the impact of these disruptions, specifically by minimizing delay propagation. We model the problem of coordinating traffic management across multiple control areas as a two-level optimization problem. Lower-level controllers, or dispatchers, manage train schedules and routes within their respective areas, while the upper-level controller, or coordinator, optimizes traffic and ensures the compatibility of dispatchers' decisions across areas. Building on our previous research (Yi et al., 2022), this work introduces a new approach to the coordinator algorithm using a constraint programming model. We've also enhanced the iterative algorithm to optimize search tree efficiency. Our methodology includes a comparative analysis of two distinct search strategies. In addition to comparing these two strategies, we also benchmarked our approach against a well-known, fully microscopic method to evaluate its effectiveness. This comprehensive evaluation provides insight into the relative performance and potential advantages of our proposed method.

Unlocking hidden potential: Digital Optimization of Train Network Resources

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Maximizing rail capacity to meet rising demands requires a strategic blend of adding new infrastructure and optimizing the use of existing assets. Operating in highly utilized networks presents challenges, as even minor disruptions can lead to significant schedule impacts. Intelligent traffic management systems help infrastructure managers improve network performance and make optimal use of available resources. These systems serve as the nerve center of train operations, integrating real-time data and advanced algorithms to manage and optimize train movements. By leveraging digital technologies, traffic management systems can dynamically adjust timetables, respond to disruptions, and ensure smooth network operations. A key feature of advanced dispatching systems is their ability to provide real-time visibility of all train positions. This comprehensive overview allows dispatchers to monitor the entire network and make informed decisions swiftly. The system can forecast train movements, predict potential conflicts, and suggest optimal dispatching measures, ensuring minimal disruption to services. Conflict resolution is another critical component of digital dispatching systems. By analyzing current network conditions, these systems can generate conflict-free plans that optimize the entire network. This includes preventing deadlocks, considering track blockages, and adapting to temporary speed restrictions. Such capabilities ensure that the network remains resilient and efficient, even under challenging conditions.

Time: Thursday, 03/Apr/2025: 9:00am - 11:00am · *Location:* POT/251/H
Session Chair: Thomas White

Railways Accident Report Text Classification using Natural Language Processing

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Efficiently learning from past railway accidents is paramount in the proactive management of railway safety and accident prevention. Historically, dedicated inquiry committees have meticulously analysed evidence, track measurements and statements from employees and eyewitnesses to generate extensive text-based accident investigation reports. However, due to a paucity of effective tools for mining and analysing this valuable textual data, the potential of these reports for guiding preventive strategies has been underutilized. We propose a study to compare machine learning models based on Natural Language Processing (NLP) techniques in response to this challenge. Our study performs an in-depth analysis of these reports, understand their underlying features, and predicting accident causes and the respective responsible departments. The primary objective of this study is to demonstrate the potential of artificial intelligence in processing and learning from past accident data. We strive to create a method that analyses the outcomes of previous investigations and aids in decision-making at policy acceptance levels. Our proposed system has a potential to reinforce railway safety management protocols. This innovative use of NLP promises a new frontier in enhancing the safety standards of the railway industry.

Analysis of Approximation Schemes for Stochastic Delay Propagation in Railway Systems

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Railway operations frequently experience delays due to the highly interconnected nature of the scheduled traffic. Precise modelling and prediction of train delays are essential for ensuring optimal capacity utilization and improving service quality. Stochastic activity networks provide a well-established approach for predictive modelling of delay propagation, which captures the interdependencies among trains by modeling the distribution of train delays allowing to obtain the full statistics of their arrival and departure times at stations. However, handling complete distributions becomes impractical for large networks because the size of the random variables significantly increases, leading to issues with overflow and high computation times. Consequently, approximation schemes allowing for model reduction are essential for practical implementations. In this paper, we analyze a discrete stochastic delay propagation model to analyze the impact of different approximation and aggregation techniques and precisions for model reduction. We discuss the effects of (re-)discretization and compare the efficiency and quality in various scenarios, also introducing and discussing the tightness of error bounds on the discretization. A test case based on a timetable for a region in Northern Germany is presented, highlighting how the choice of the right approximation method can serve as a useful assessment tool during the timetable planning phase.

Analyzing the Impacts of Railway Accident/Incident-Induced Delay – A Tripod Approach

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Evaluation of the impacts of train delay during railway accidents and incidents is essential for understanding the operational performance of a railway system. Delay time has traditionally been used as a measure of train delay but may not have properly reflected the influence of these delay events from fleet management and service perspectives. In this paper, a tripod approach is developed to evaluate the impact of accident/incident-induced train delay based on total delay time, number of delayed trains, and number of affected passengers. A case study is presented using empirical accident and incident data from Taiwan's conventional railway system to demonstrate the strengths of this model. The results showed that different train delay measures may show differing trends when evaluating train delay by track type, train type, and accident/incident type, and less used delay measures such as number of passengers delayed can sometimes reveal valuable information regarding the impact of train accident and incidents. The methodology provides a more comprehensive and graphical presentation of the consequences of train delay events using a three-way radar chart. This research is novel for its original evaluation method for train delay and can assist in more effective assessment of railway accident/incident consequences.

Development of Algorithms for an Automated Completeness Review of ETCS L2 Data Point Plans

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To support the rapid rollout of the European Train Control System Level 2 on the German railway network, this paper outlines a step towards automating the data point plan review process. It includes the collection of requirements, the investigation methods and an approach for the development of algorithms for an automated completeness review of ETCS L2 data point plans. The approach proposes to use a combination of different methods for rule-based and knowledge-based formalization, facilitating the integration of process understanding and domain expertise. In accordance with the gathered functional and non-functional requirements, the developed approach supports the development of algorithms for an automated completeness review of any given plan. The modular structure allows for easy maintenance and efficient use. The developed approach is used to exemplarily develop algorithms for the automated completeness review of DP plans for exits of ETCS L2 and the developed algorithms are manually applied to two different infrastructure layouts. Based on the findings of the research, development and possible application, complementary components that facilitate the integration of the developed algorithms into an overall automated review of ETCS L2 DP plans as well as possible further development steps that enhance the developed approach are suggested. The implementation of the developed algorithms will provide support for human plan reviewers, leading to an acceleration of the planning and rollout process of the European Train Control System in Germany, contributing to interoperability and thus increasing the railway capacity in Europe.

Enhanced Template-Based Voting Logic for Dual Train Detection Systems with Integrated Self-Diagnostics and Multiple-Component Fault Tolerance

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A train detection system is vital for railway operations and safety, as the braking distance exceeds sight distance. Detection errors can result in signaling deficiencies and potential collisions, such as the near-miss incident at Jiadong station on August 28, 2019. Taiwan Railway employs a fixed-block signaling system with two axle counter systems within each block. Discrepancies between these detection systems present challenges for accurate train detection. Various decision logics have been implemented: serial connection meets fail-safe requirements but reduces efficiency, parallel connection enhances reliability but compromises safety, and primary-secondary configuration can lead to underutilized systems. This study introduces an "Enhanced Template-Based Voting Logic (ETVL)" to improve the safety and efficiency of dual train detection systems by fully leveraging self-diagnosis capabilities and addressing multiple simultaneous component failures. ETVL employs a “Template Construction Module” to create comprehensive templates of all possible occupancy statuses by simulating trains passing through the corresponding track, including both accurate and failure scenarios. The “Occupancy Matching Module” then matches actual train occupancy statuses with the preconstructed templates and information from the self-diagnosis system. Case study results demonstrate that ETVL outperforms existing logics in terms of reliability and safety. Implementing this logic can significantly enhance the reliability and safety of dual train detection systems.

Modeling equipment-level topology of railway yard from 2D vector Graphic

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Railway yard models are replication of the physical layout and logical functions of the yard, striving for greater precision and closer alignment with actual use scenarios. Modeling railway yard properly is crucial for optimization and simulation studies. However, most existing research relies on simplified yard models that consider only topological relationships, ignoring the potential errors from physical properties of equipment, which is not conducive to obtaining conclusions that closely match real-world situations. Therefore, establishing a equipment-level topology model is essential for the railway yard model to better supporting academic problem research and assist operation management. The paper proposes a 2D graphics-based yard modeling method that takes the yard’s design documents (stored in DXF files) as input and directly outputs the yard’s equipment-level topology model. This method consists of five stages: (1) locating yard equipment based on design documents; (2) identifying equipment types based on equipment location; (3) recognizing the pose of equipment; (4) obtaining the standard turnout size based on tracks information; (5) calculating the yard’s topology graphs. Experiment show the obtained yard’s equipment-level topology model can correctly extract basic attributes of the equipment within the yard and construct topological relationships based on these attributes. Due to the more thorough consideration of equipment information, the topology model proposed in this paper offers more detailed insights into the equipment attributes and space required for trains to complete various tasks within railway yards, ensuring the model’s practical applicability.

THU-1-D: Station Capacity and Passenger Flows

Time: Thursday, 03/Apr/2025: 9:00am - 11:00am · *Location:* POT/361/H
Session Chair: Francesco Corman

Train Platforming Problem from the Viewpoint of Passenger Flow Management

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This paper addresses the problem of train platforming problem (TPP) from the viewpoint of passenger management. Currently, the train platforming decision and the passenger management decision are done separately. However, as the train platforming decision can have a significant influence on the path that each group of passengers takes in the station area; hence, the passenger flow in the station should be taken to account when making a platforming decision. In this study, this problem is defined as the Train Platforming and Passenger Management Problem (TPPMP). We propose modelling the TPPMP using a mixed integer linear programming (MILP) formulation. Our case study result suggests that the passenger flow in the station can be improved significantly when trains are allowed to be reassigned to different platforms.

Dwell Time Scale Optimization for Urban Rail Transit Based on Passenger Boarding and Alighting Data Using Improved Fisher Clustering Method

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For the improvement of the overall transportation capacity and service quality of train timetables, this paper establishes a refined dwell time scale optimization method based on the analysis of passenger boarding and alighting demand focusing on the busiest door of the train. Firstly, a SMOTE-XGBoost oversampling method is used to expand the imbalanced collected actual data. By comparing among the classic train dwell time regression models, a train dwell time regression model is proposed under the consideration of the passenger volume, full load rates of the train and the proportion of passengers boarding and alighting at the busiest door. To gain the refined train dwell time segments and scales, an improved clustering method based on Fisher clustering method is developed considering the practical feasibility constraints of timetabling including the minimum length of time segments and minimum values of dwell time scales. The optimal segment numbers are determined through elbow method and time difference method. Finally, the effectiveness of the optimization method is verified by taking Shanghai Metro Line 13 as an empirical case. The results show that compared with the current train dwell time scales, the optimized dwell time scales can better identify the changes in dwell time demands with the average error reduced by about 2 seconds. On the timetabling level, the optimized train dwell time scales can increase the transportation capacity of peak hours by about 2\% for saving the average train travel time by over 1 minute.

Spatio-temporal Transfer Learning Hypergraph Convolutional Neural Network for Network-Wide Metro origin-destination passenger flow prediction with new suburban rail lines

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To alleviate metro operational pressure, suburban rail lines are actively being promoted. Comprehensive OD passenger flow prediction that considers newly constructed suburban rail lines is essential for new line planning and efficient network operation. However, OD flow prediction is challenging due to the lack of historical passenger data for new lines and the intricate relationships among existing OD pairs. This study employs hypergraphs to represent the complex interrelationships between OD pairs and proposes a hypergraph convolutional neural network based on transfer learning with spatio-temporal features (ST-TLHGCN) for OD flow prediction with new lines. In the proposed framework, spatial features of OD flows are captured based on geographic data, while transfer learning enables the sharing and updating of temporal features among OD pairs within the same hyperedge, addressing the absence of passenger data for new lines. Hypergraph convolution neural network is then used to extract OD flow patterns and spatiotemporal features within each hypergraph, achieving network-wide OD flow prediction. A case study on the Shanghai metro system, including newly constructed suburban lines, demonstrates the effectiveness of the ST-TLHGCN model, demonstrating better prediction accuracy. Furthermore, the hypergraph construction of OD pairs based on spatiote-mporal features and the ST-TLHGCN model can support for new line planning and network operations.

Passenger Demand Management in Public transit Systems Considering Crowding Effects

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This study addresses the growing challenges in railway transportation caused by unpredictable passenger demand. We developed a two-stage scenario-based programming model to improve the robustness and adaptability of train timetable rescheduling (TTR). In our experiments, we tested the model under several demand scenarios, ranging from moderate (1500 passengers, with minimal crowding) to very high (up to 6250 passengers), and compared the results with those from a traditional deterministic model. The scenario-based approach proved effective in optimizing train schedules and managing passenger flow, particularly under conditions of fluctuating demand. The findings highlight the importance of addressing demand uncertainty, as variations in passenger volumes significantly impact scheduling and capacity utilization. The model demonstrates potential for enhancing operational efficiency and passenger satisfaction, though further validation with real-world data is essential to fully realize its benefits. By incorporating scenario-based demand adjustments, this approach offers a resilient solution to urban transportation challenges, supporting better train operation management and improved service reliability.

Multilayered Railway Passenger Demand Estimation Considering Nested Choices: A Computational Graph-based Learning Framework

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This paper attempts to develop a systematic and theoretically consistent machine learning model to quantify and estimate multi-level railway passenger demand, capturing overall demand patterns. This includes estimating boarding and alighting passengers at stations along a corridor, origin-destination (OD) trips between stations, and passenger flows loaded onto train lines and corresponding train line segments. Observations are transformed into loss functions and mapped onto a hierarchical flow network to simultaneously estimate these multilayered demand variables. By incorporating a Nested Logit (NL) model into the hierarchical flow network, the learning model can further calibrate a series of interpretable parameters associated with key attributes in rail line planning (e.g., line frequency, fare levels, and travel time), enabling policy-sensitive analyses. Unlike pure discrete choice models, the proposed estimation model is constrained by line-based capacity constraints to prevent passenger flow overload on

Train Dwell Time Models for High-Passenger-Volume Stations Using a Bivariate Distribution Function

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Train dwell times in high-passenger-volume stations are complex and inconsistent due to variations in passenger behaviour and interactions. While several studies have examined factors affecting dwell time and developed models to predict it, these models often struggle to accurately predict dwell times under high passenger volume conditions. Consequently, dwell time predictions are often unreliable, making it difficult to plan effective timetables in crowded environments. Given this variability, using probability-based approaches to predict dwell time delay could provide better planning. Although some studies have identified dwell time probability distribution functions, they generally do not include passenger volume level as a variable, limiting their applicability in high-density stations. To address this gap, this research investigates dwell times specifically at high-passenger-volume stations, using actual operational data to highlight the limitations of current dwell time models. Based on these insights, it proposes a bivariate probability function that incorporates passenger volume as a key variable, providing a more reliable framework for predicting dwell time delays in crowded environments. The reliability of this bivariate function is validated, showing its capacity to predict the probability of achieving target dwell times, which is essential for planning dwell times. Furthermore, this model can be applied alongside delay impact assessments, facilitating a further risk evaluation framework that can be used to make more informed decisions when setting dwell times in timetables.

FRI-1-A: Timetabling and Scheduling 4

Time: Friday, 04/Apr/2025: 9:00am - 11:00am · *Location:* POT/051/H
Session Chair: Christian Liebchen

An iterative heuristic for strategic timetabling with integrated passenger routing in railway networks

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Periodic timetabling is a crucial but computationally challenging problem in the railway planning field. Existing approaches often overlook the interaction between passenger routes and timetables, leading to suboptimal solutions. In this paper, we propose a method that incorporates passenger routing into the optimization of periodic timetables. Our goal is to optimize the periodic timetable from the strategic planning perspective, aiming to minimize the total perceived passenger travel time. We propose an iterative heuristic approach that integrates an adaptive large neighborhood search algorithm with a mixed-integer linear programming solver. To improve the efficiency of the algorithm, we design tailored operators and an outer loop. We conduct real-world case studies on real-life instances of Netherlands Railways to illustrate the effectiveness of our approach. The computational results show that our solution method is capable of addressing real-life problems.

Examining the Impact of the Level of Detail in Railway Infrastructure Modeling on Timetable Optimization

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Different levels of detail can be used to model a railway network when optimizing the timetable. While microscopic models are required to accurately represent the train operations, they are often quite complex and require long computation times. Therefore, macroscopic models are often used instead. Microscopic simulation is then used in a later stage to determine if the timetable is conflict-free. In this work, we examine the impact of the level of detail that is used to model the network on the optimization of the timetable, more specifically on improving the timetable robustness. This way, we obtain more insight into which level of detail is most useful in practice in terms of the quality of the solution and the computation time. To do this, four different network representations with an increasing level of detail are considered. This includes a macroscopic, two mesoscopic and a microscopic representation. For each of these representations, we formulate a mathematical model to optimize the robustness of the timetable. These models are applied to a line on the Swedish network. The results show that including more details in the optimization leads to better solutions compared to optimizing with less details and solving the conflicts in a later stage. Surprisingly, for our experiments, including more details actually led to a significant decrease in the computation times.

Research on Traffic Organization Optimization of Xi'an Metro Line 14 and Joint Operation Scheme of Line 12

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Firstly, taking Xi'an Metro Line 14 as an example, we analyse the current and future passenger flow characteristics based on the spatial and temporal distribution of passenger flow across the line sections. We also calculate the imbalance coefficients and conclude that under uneven distribution of passenger flow, the line can adopt a train operation plan with the full-length and short-turn routing. Secondly, taking Xi'an Metro Line 14 as an example, an optimization model for the full-length and short-turn routing of urban rail transit is constructed, considering the constraints such as departure frequency, departure interval, sections included in the routing, restrictions of turn-back stations, train quantity, and occupancy rate. The optimization objective is to minimize passenger travel cost. The decision variables are the train operation frequency for each routing and the location of turn-back stations for the short-turn routing. The genetic algorithm is selected and programmed to solve the model, thus optimizing the train operation plan for urban rail transit with the full-length and short-turn routing. Finally, taking Line 14 and the first phase of Line 12 as examples, considering the constraints such as departure frequency and departure interval, a model for the joint operation of urban rail transit is constructed with the optimization objective of minimizing both passenger travel cost and operating enterprise cost. The decision variable is the train operation frequency, which is solved using the enumeration method. This approach enables us to propose a scheme for the joint operation of urban rail transit.

Incorporation of Automatic Scheduling within a New Annual Timetable Process for a Railway Infrastructure Manager

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In this article, we present the impacts of fulfilling the requirements of the European Parliament's Directive establishing a single European railway area (Annex VII of Directive 2012/34/EU) on the Annual Timetable Process of DB InfraGO, Germany's largest railway infrastructure provider. Compared to the recent planning procedures, it is requested by Annex VII to include approximately ten times more temporary capacity restrictions for construction works in the Annual Timetable Process resulting in a much more complex planning problem. Consequently, a modified planning procedure and modified mechanisms for solving conflicts are needed. We discuss our approach to establishing a new process that fully integrates our automatic timetabling algorithms. The complexity of using these algorithms is highlighted, both in terms of handling the quality of the data used and the changes it will bring to our timetable planning staff. Results from first simulation exercises are provided to demonstrate an effective way of introducing a new process that integrates algorithms.

On the Automatic Resolution of Microscopic Conflicts in Mesoscopic Timetables

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The manual resolution of microscopic conflicts in mesoscopic timetables, supported by microscopic services, as proposed in the MoD architecture (Glaus and von Olnhausen, 2019) comes with considerable effort for the timetable planner. To enable significant efficiency gains during this manual work, an algorithm for automated local microscopic conflict resolution is presented in this paper. This algorithm solves conflicts through microscopic rerouting and the adjustment of running and stopping time supplements. Our core idea is to combine a microscopic and mesoscopic railway model in a single MILP through a technique called coupling relations. Occupations of microscopic infrastructure elements, i. e. signal blocks, are explicitly modeled and their start and end times are approximated dependent on arrival and departure times, stopping and running time supplements at the mesoscopic level through a linear regression model. This enables the use of a lightweight microscopic model embedded in a mesoscopic one. Using these approximations our model eliminates overlapping occupations of the same infrastructure element by two or more trains to ensure a conflict-free timetable. The computation of the regression model is performed using calls to an external microscopic occupation calculator. Numerical results show that the coupling method presented allows for good approximations of the occupations while the algorithm achieves acceptable computation times, and has potential for the use in an interactive decision support system. The system is designed in a generic way so that it can be used with different implementations of occupation calculators and railway systems operating in different countries.

Solving large-scale railway scheduling problems with automated and assisted driving systems

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The railway scheduling problem concerns the determination of trains' scheduled departure and arrival times at stops, and the allocation of capacity in the network. The timetable must be both conflict-free given infrastructure constraints, and stable enough for trains to recover from delays that could occur in normal operations. Existing methods for tactical scheduling contain a trade-off between having an accurate (microscopic) representation of signalling constraints, and having a simple-enough (macroscopic) infrastructure representation to scale to real-world problem instances. This creates issues for infrastructure managers looking to run more trains on their infrastructure by migrating to Distance-To-Go (DTG) signalling systems (e.g. ETCS Level 2), and to exploit the capabilities of Connected Driver Advisory Systems (C-DAS) and Automatic Train Operation (ATO) to control trains more precisely. In this paper, we present a methodology for incorporating the capabilities of DTG signalling in conjunction with C-DAS and ATO systems into a disjunctive scheduling model for both periodic and nonperiodic instances. We show that the resulting model has both a microscopic infrastructure representation, and a macroscopic computational complexity, allowing railways to quickly compute conflict-free and stable timetables for large problem instances. The resulting model also accurately represents the computation of the brake indication point for both conventional and DTG signalling as a function of the trains' current speed. Tests on a large-scale periodic scheduling instance in the UK show that the model produces timetables with reasonable computation time.

FRI-1-B: Disruption Management

Time: Friday, 04/Apr/2025: 9:00am - 11:00am · *Location:* POT/151/H
Session Chair: Rob Goverde

Recent Advances in Algorithmic Approaches in Integrated Disruption Recovery in Railway Systems

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This paper reviews recent advances in algorithmic approaches in integrated disruption recovery problems in railway systems. With recent improvements in computational power, there has been an increased focus on solving integrated problems, such as train rescheduling combined with rolling stock rescheduling. This trend results in increased difficulty and computational challenges compared to solving those problems separately, consequently requiring novel methods and very efficient solution processes. Furthermore, we explore related works in the field of disruption recovery in air transport. Besides, recent works have addressed the application of machine learning techniques in related transportation problems enhancing optimization algorithms with promising results, which allow scaling up problem instances and/or speeding up the computational process to deliver fast solutions in real-time.

Quantitative Assessment of Resilience in Rail Station Areas: Effects of Targeted Infrastructural Upgrades

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Rail stations are critical components of the railway network, facilitating high passenger mobility with substantial traffic flows. However, the station area and its vicinity are particularly more vulnerable to disruptions due to the dense concentration of dynamic operational elements. This complexity introduces significant challenges to maintaining the rail network resilience, as requent train movements and passenger flows amplify the risk of operational interruptions. Previous studies have primarily focused on analysing networkwide resilience, often overlooking the critical role of station areas and their specific topographical features in maintaining overall system stability. This study investigates the impact of localized infrastructure modifications within station areas on system resilience during disruptions. The mesoscopic approach evaluates the impact station-specific elements, such as platform configurations, switch positions and signaling systems, on operational performance under various disruption scenarios. The results indicate that resilience is highly sensitive to disruption type, time, and duration. The findings offers a practical framework for infrastructure managers to assess on resilience improvement with reference to infrastructural planning and taking informed decisions.

Train rescheduling in disrupted high-speed railway operations: a progressive multi-granularity time-space network based method

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The train rescheduling problem under disruptions has long posed significant challenges for railway operations, particularly in large-scale networks characterized by extended durations, uncertain disruption information, and the necessity for vehicle circulation rescheduling. This paper introduces a time-phased rescheduling methodology to address the real-world disruption management problem. We formulate the problem as an integer programming model aimed at minimizing time delays, vehicle circulation rescheduling costs, and cancellation costs on a mixed-resolution time-space network. This network employs two time phases to ensure solution feasibility in the near future while reducing the overall problem scale, incorporating different temporal and spatial granularities, rescheduling measures, objectives, and focuses. A rolling horizon solution framework and a Lagrangian relaxation algorithm are proposed to solve the problem. A real-world instance is employed to evaluate the performance of our methodology.

Researching of timetable and rolling stock circulation for a bi-directional disrupted metro line with the flexible train composition strategy

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Real-time train scheduling is inevitably affected by various uncontrollable factors, which can lead to disruptions under severe interference. This study addresses the rescheduling problem of operational disruptions in scenarios where flexible train composition strategy and unpaired operation mode are jointly applied. We propose a multi-objective mixed-integer linear programming (MILP) model to derive new train timetables and rolling stock circulation plans. The model aims to minimize deviations from the planned timetable, the number of cancellations, and deviations from the planned coupling/decoupling plan. Additionally, our paper introduces a new rescheduling measure—flexible rolling stock composition—allowing train services to be coupled/decoupled at turn-around and adaptation stations. This measure aims to resolve rolling stock conflicts caused by train disruptions under unpaired operation conditions. Computational results demonstrate that our approach significantly reduces the number of train cancellations by 60$\%$ and deviations from the planned coupling/decoupling plan by approximately 20$\%$. Moreover, it effectively balances passenger demand with capacity supply, particularly in scenarios where train services operate in unpaired modes.

Rescheduling trains on a metro line with one-way disruption considering multiple short-turning routes and alternative directions operations

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The metro system is facing increasingly unexpected events, which may cause disruptions, resulting train delays. Comprehensively applying train rescheduling strategies can maintain the capacity to the maximum extent and accelerate traffic recovery. This paper focuses on one-way disruptions and studies a train rescheduling problem considering multiple short-turning routes and alternative direction operations under limited track resources. We use a mesoscopic topology to describe the trains' available routes. A mixed integer linear programming model with path selection, rolling stock circulation, and conflict resolution constraints is proposed to build an optimized train schedule with known disruption. To describe the train route modification during the rescheduling period, the model involves a set of binary variables indicating whether a train passes by, executes short-turning, or moves from/to the adjacent depot at a certain station. For solving a large-scale problem, a rolling horizon algorithm framework with a sophisticated cross-rolling-time-windows consistency preservation technique is employed. A case study is conducted based on practical data on the Guangzhou metro. The rolling horizon algorithm can provide a rescheduled timetable faster than the traditional solution algorithm using Gurobi. The multiple routes ensure that train services are maintained at a low transportation capacity. Long-route trains operating in alternative directions are regularly generated during the disrupted period, ensuring accessibility between the both sides of the disrupted section.

Multimodal passenger-centered network vulnerability assessment using a path-based disruption management model

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Determining impact of multimodality on network disruption management is essential for creating our future, sustainable transportation networks This paper thus presents the multimodal vulnerability network model (MVNM), which determines the critical links of a multimodal network w. r. t. passenger routing and disruption management of the corresponding services. Therefore, we extend the existing railway network vulnerability model by Szymula and Bešinovi´c (2020) by adding a path-based disruption management approach to optimally adjust the operating services under disruptions. The resulting MVNM is solved by combining multi-column generation and row generation, to iteratively identify beneficial passenger routes, disruption management measures and crucial timetabling constraints. The MNVM is then applied on a case study of the long distance air and rail network of Spain. The results show, that multimodality increases the served demands and the survivability of a network, the latter particuarly for several simultaneous disruptions. However, multimodal networks appear to be more vulnerable for few disruptions, comparing their unimodal counterparts. The detailed effects of multimodality on passenger routing are to be investigated further, Also, the explicit consideration of the timetable dependencies of passenger routing could further improve the MNVMs passenger focus and thus the realism of the obtained results.

FRI-1-C: Freight Operations

Time: Friday, 04/Apr/2025: 9:00am - 11:00am · *Location:* POT/251/H
Session Chair: Carlo Mannino

Optimizing train dispatching for the Union Pacific Railroad

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Union Pacific (UP) is one of the largest transportation companies in the world, with over 50.000 kms of rail network covering 23 states in the United States. In 2017 Union Pacific embarked on a project that within 5 years would lead it to become the only rail operator in the world equipped with a technology capable of fully automating the real-time management and optimization of train traffic. In 2021 the main milestone of such project has been reached with the first deployment of the automated dispatching system we present here. To attack such large and complex problem, we decomposed it into distinct but interrelated functional components, and developed optimization models and methods to handle such components. The models communicate with each other through variables and constraints, and by a careful timing of invocations. In this paper we give an overview of the overall approach.

Railcar shunting in a flat rail yard using an extended bitstring-encoded schedule representation

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This article focuses on the railcar shunting in a flat rail yard, which lies on finding an optimal shunting schedule that can rearrange one train in right order. In this problem, a shoving strategy is used, which the shunter moves railcars backward to clear a switch, then pushes them onto a different track, leaving part of the railcars decoupled. To solve the problem, we extend the existing bitstring encoding method, in which feasible shunting schedules can be induced by two binary matrices: bitstring matrix and sorting track assignment matrix. By this way, the original problem is transformed into a binary encoding problem which aims at finding two optimal binary matrices. Then, to find the matrices, we propose a mixed integer liner programming model (MILP) which minimizes the time-consumption required for shunting schedule. Considering the computational complexity of this model, we design a two-stage algorithm to improve the solving efficiency. In the first stage, we build two binary integer linear programming models, alongside three emprical rules to find the optimal bitstring matrix. In the second stage, a heuristic rule is developed to determine the optimal sorting track assignment matrix. To valid our proposed model and algorithm, computational experiments are conducted on a set of different-scale instances. The results show that the two-stage algorithm can get (near-)optimal solutions within 1 second. Besides, sensitivity analyses on the number of sorting tracks is also conducted to gain more managerial insights.

The Periodic Yard Saturation Problem

Roberto Mancini[3], Gianpaolo Oriolo[2], Veronica Piccialli[1], Anna Russo Russo[2], Davide Ussai[3]
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To increase rail freight transportation in Italy, Rete Ferroviaria Italiana (RFI) the Italian railway infrastructure manager, is carrying out several investment plans to enhance transshipment yards, that act as an interface between the rail and road networks. The need is to increase their practical capacity, i.e. the maximum number of trains that can be inserted without altering the current timetable while respecting all relevant constraints. In this paper, we therefore define a suitable saturation problem that we call the {\em Periodic Yard Saturation Problem} (pysp). A solution to pysp returns both the set of trains that can be added to the timetable and operational details, such as routes and schedules, that are necessary to implement the new timetable. On top of that, a solution is also requested to be periodic as periodic timetables and schedules keep the daily management of the yard easier. For the solution of pysp we propose a solution approach that is based on the solution of a Mixed Integer Linear Program and exploits non-trivial mathematical programming techniques such as row and column generation. Both the model and the solution approach are validated on a real Italian transshipment yard, located at Marzaglia, on different scenarios corresponding to different investment plans of RFI. The results show that already in the current scenario it is possible to increase the number of weekly trains by 17%, while proper investments allow to double the number of weekly trains with a timetable that has a periodicity of a day.

Revenue management for intercontinental rail freight transport

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China-Europe rail freight has emerged as a vital component of the global supply chain in recent years. However, the COVID-19 pandemic and the Red Sea crisis have strained the China-Europe Rail Express (CRE) network, leading to a surge in ad hoc demand that challenges its limited capacity. Leveraging ad hoc demand through auction-based mechanisms presents an opportunity to increase revenue, yet revenue management in the railway freight industry has received less attention compared to the airline sector. To address these challenges, this paper introduces the RM-ISSND model, a novel decision support system designed to optimize revenue management in intercontinental rail freight. The model integrates key elements of rail transport, including transshipment at border-crossing terminals, order splitting, a rejection mechanism, and the scheduling synchronization of multiple containers across different rail systems. The model effectively selects ad hoc demands for intercontinental rail freight while rejecting shipments that would be more efficiently managed by maritime or air transport. This research offers valuable insights for enhancing service design and revenue management in the intercontinental rail freight industry.

Practical Challenges in Optimizing Production Schedules in Classification Yards

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Classification yards are the hubs of single wagonload networks where inbound trains are disassembled, railcars get sorted and new outbound trains are built. In the large-scale facilities, multiple processes need to be carried out by numerous resources including staff, locomotives and tracks. For efficient operations in the classification yards, planning the production schedules plays an important role. This task is mainly carried out by experienced planners with limited computer-based support. The German rail freight company DB Cargo AG therefore intends to implement an integrated planning system applying mathematical optimization to generate production schedules. In this paper, we present a formulation of the resource constrained project scheduling problem and discuss additional requirements for the practical usability of the model. Furthermore, we present a tailored heuristic to solve the complex planning problem and apply it to a real-world problem instance.

FRI-1-D: Maintenance and Infrastructure Performance

Time: Friday, 04/Apr/2025: 9:00am - 11:00am · *Location:* POT/361/H
Session Chair: Steven Harrod

Track Component Failure Detection Using Data Analytics over existing STDS Track Circuit data

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Track Circuits (TC) are the main signalling devices used to detect the presence of a train on a rail track. It has been used since the 19th century and nowadays there are many types depending on the technology. As a general classification, Track Circuits can be divided into 2 main groups, DC (Direct Current) and AC (Alternating Current) circuits. This work is focused on a particular AC track circuit, called "Smart Train Detection System" (STDS), designed with both high and low-frequency bands. The main purpose of the proposed work is to detect anomalies before any part of the track circuit fails, leading to a pre-emptive maintenance action. Our approach is to use STDS current data applied to a convolutional autoencoder as an anomaly detector, then an SVM (support vector machine) classifier when there is an anomaly as a type of failure identifier, and finally a regression model to predict the approximate time of failure when there is a degrading pattern. This ensemble of models makes the system compatible with the ISO-17359 standard. Models were trained to detect 15 different anomalies that belong to 3 more general categories. The method was tested with field data from 10 different track circuits and validated by the STDS track circuit expert and maintainers. All use cases were successfully detected and correctly classified by the method.

Establishing a regime to managing reinvestment planning on a no-longer brand-new Metro System: Reinvestment value modelling and asset degradation modelling

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When a brand-new Metro system reaches an age where a number of assets approach end-of-life and is beginning to face major reinvestment projects, a new approach is needed to ensure that reinvestments are prioritised holistically with full respect to main company metrics. The existing Operation & Maintenance setup supplemented with an excel based project prioritisation will probably struggle to do this. Facing this situation, the Copenhagen Metro has introduced an Asset Investment Planning tool aimed at producing such holistic overview of the impact to the overall company metrics; Customer Satisfaction, Service Availability and Safety thus allowing a transparent and data driven re-investment project prioritisation with a long time horizon. The tool includes an Investment Value Model as well as and Asset Degradation Model covering all asset groups and all reinvestment projects. The tool provides an overview of the optimal time to replace assets as failures rate increase due to age i.e. answering the question of which reinvestments can wait and which cannot wait. Also, the models enable the evaluation of project allowing the prioritisation of reinvestments providing the largest benefit to the company. Key considerations for the modelling framework was simplicity and completeness; models should cover all asset groups and systems and should be transparent. Alignment with surrounding processes was also a key factor as was alignment with overall company metrics. Data availability has promoted simpler and more general models. Paper concludes that this structured approach is viable, that completeness, simplicity and model transparency are key factors for success.

The hidden cost of switch failures: the impact of subthreshold delays

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Switches and Crossings are a notorious source of disruptions and delays on many railway networks due to frequent breakdowns – suggesting sub-optimal maintenance strategies. In this study, the extent to which delay costs, as a major component of life cycle modeling, are fully accounted for by delay attribution data is evaluated. Using historical operation data for the Swedish railway network, annual estimates of switch-attributed delays are compared with estimates derived from two approaches: a simple heuristic that aggregates all delays at a location when there is a switch failure and causal inference by propensity score matching. Results showed that for the same failures within the study period, switch-attributed delays only constituted 6.4% of delays derived from the heuristic and 14.8% of delays estimated by causal inference. Adopting causal inference as a more conservative estimation of delays from switches, the discrepancy in reporting delays translates into unaccounted social costs in the range of 270 and 1125 million SEK (~€231m – ~€963m) and an underreporting of 17.5 to 72.8 million SEK (~€1.4m – ~€6.1m) of penalty costs. This study is a first step towards developing a more robust way of estimating the impact of switch failures and any other failures on train delays.

Development of Train Operation Risk Assessment Framework Based on a Data-Driven Bayesian Network

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Following the two recent high-profile train accidents in Taiwan, there has been an increased public awareness of the importance of risk management in train operations. Some of the severe train accidents were caused by abnormal operation of trains or defective train control and other in-train systems. To address these operational uncertainties, this research proposes a six-phase approach that integrates the Human Factors Analysis and Classification System with Bayesian networks to develop a quantitative risk assessment framework. The approach starts with identifying potential risk events through accident data and performing causal analysis to further identify risk factors that may contribute to the occurrence of the risk events. A Bayesian network constructed using historical Automatic Train Protection (ATP) data quantifies the relationships between various risk factors while calculating the probabilities of risk events. The results show that the framework can predict track-section-specific risks by using past train operational information and railway route details. The model can be implemented to enhance driver's situational awareness by informing drivers the risk levels of different track sections in advance, which enables proactive preparation, potentially improving the overall safety of train operations by ensuring that drivers are well-informed and able to respond effectively to varying risk conditions.

CVCM Track Circuits Pre-emptive Failure Diagnostics for Predictive Maintenance Using Deep Neural Networks

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Track circuits are crucial for railway operations. They are the main signalling sub-system used to locate trains within track segments. Continuous Variable Current Modulation (CVCM) is one of such track circuit technologies. As with any equipment deployed on field, this safety critical component may experience failures, provoking cascading blockages of operations. Most such failures develop first from an anomaly into a critical state over time. These anomalies are usually reflected in the monitored signals, though not always visually distinguishable. Conventional approaches, which typically rely on such prominent changes in the signal, therefore fail to identify failures beforehand. Detecting anomalies at early stages before they evolve into failures, and subsequently predicting failure types, with time to failure estimation is of high im- portance. It allows for improved maintenance planning, minimizing time and revenue loss from operational disruptions. Leveraging deep neural networks, we propose our new methodology for predictive maintenance to detect, classify and estimate sufficiently in advance the time and type of failures. We demonstrate our method's efficacy on 10 failure cases for CVCM, independent of installation location or configurations. Our method is ISO-17359 compliant and especially successful in improving early-stage anomaly detection compared to conventional approaches, which is paramount for effective predictive maintenance. We achieve solid operational performance with promising results: 99.99% true positive rate for anomalies detected, 99.31% overall classification accuracy across all failure types, successful early-stage detection averaging below 1% into start of anomaly development in signals. Finally, utilizing conformal prediction techniques we provide accompanying uncertainty quantification metric for maintainers to measure model confidence in a particular prediction, where we reach 99% confidence, with sufficient coverage at each failure class. Given CVCM is deployed in various urban settings worldwide, our research holds signifi- cant relevance for maintenance personnel in improving reliability of railway operations through predictive maintenance.

FerroMoRA: an application website for automatic recreation of railway horizontal alignments

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In this paper, an innovative tool (FerroMoRA) designed to help engineers address the problem of obtaining an optimal recreated horizontal alignment for an existing railway line is presented. Based on mathematical optimization, this tool implemented as an application website automatically provides a new horizontal alignment that minimize the distance with respect to the track's centerline, taking into account the technical constraints according to the operational requirements of the railway line, and the maximum lateral distance allowable considering maintenance operations. Unlike other previously proposed methods, the optimization model implemented in this tool considers mixed traffic (maximum speed for passenger trains and minimum speed for freight trains) and also a new approach to deal with the technical constraints. Generally, these requirements are expressed in terms of minimum values for radius and the length of each type of geometric element (tangents, circular curves and transition curves), assuming a predefined value of cant for circular curves. Instead, the new approach implemented in FerroMoRA consists of obtaining for each circular curve an admissible range of cant values, from which the engineers can later choose, being sure that all the technical constraints are fulfilled. FerroMoRA has been successfully tested with academic examples and also applied to several real cases in collaboration with a technical team of engineers of the Spanish engineering company INECO in order to prove its practical usefulness.

FRI-5-A: Line Planning

Time: Friday, 04/Apr/2025: 1:45pm - 3:45pm · *Location:* POT/051/H
Session Chair: Lei Nie

Determine Line Plan and Fare Pricing Strategies for Newly Constructed Lines with Dynamic Interactions of Passenger Demand with Travel Time and Ticket Costs

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This study focuses on the line planning and fare pricing problems of newly constructed or under-construction suburban railway lines, considering the relationship between demand and supply. A least-squares procedure is adopted to estimate a gravity model from historical passenger flow data, geographic data, and socioeconomic data of the existing metro network. The estimated gravity model are then adopted to capture the interdependencies between demand and supply for the newly constructed suburban railway lines. An integrated line planning optimization framework is proposed that incorporates the gravity model for demand estimation. The demand is represented by a function of the generalized travel time and ticket costs. The two costs are related to the line plan as well as the fare pricing decisions. This allows the study to flexibly consider situations in which the newly constructed railway corridors use different line-setting strategies and fare pricing strategies and appraise the contribution of specific strategy attributes to demand generation, ultimately accounting for demand generation and allocation simultaneously. Shanghai Jiading-Minhang Line and Airport Link Line are adopted to examine the proposed method. The computational results show that the accuracy of the demand forecast results has been significantly improved by considering both the supply-side and demand-side factors. The ability of train operation solutions to balance passenger demand and capacity supply has been greatly improved by embedding the interdependencies between demand and supply into the line planning optimization model.

Optimizing High-speed Railway Network Line Plan Incorporating the Newly-built Railway

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Unlike the complete line planning of the high-speed railway network, when a newly-built railway is incorporated into the high-speed railway network, it's important to consider the coordination between the newly-operated trains and the existing trains, as well as the adjustments of the existing trains. In this paper, we introduce an enhanced line planning model that is applicable to the high-speed railway network incorporating the newly-built railway. Considering the structure changes of the high-speed railway network caused by the newly-built railway, the line pool we constructed not only includes all the potential line concepts for newly-operated trains, but also adds line concepts for some existing trains, and all their potential line concepts when adjustments are needed. A joint decision-making line planning model for newly-operated trains and existing trains is established, with the model objective focused on minimizing train costs and revenue losses, and a revenue loss probability function is introduced

Benders decomposition for periodic train line planning with passenger routing

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The railway line planning problem (LPP) is essential in shaping the quality of passenger services and managing the operational costs for railway companies. Currently, China primarily employs a non-periodic train operation model, which lacks precise planning for passenger connections between non-periodic trains. This paper investigates a periodic train operation plan suitable for China's high-speed railway characteristics over large-scale networks, integrating passenger flow distribution into the optimization process. This paper proposes a train service network based on dynamic passenger flow distribution, which considers transfers and captures detailed travel routes for passengers. With its passenger-oriented, the mixed-integer model based on the train service network takes into account the influence of ticket price on passengers' route selection behavior. To tackle the challenges of large-scale problem instances, this paper proposed an improved Benders decomposition algorithm where several heuristic techniques are introduced to accelerate the computation to solve the drawbacks of classical algorithm. Numerical results showcase the good performance in the large case study of China's Shangdong high-speed railway network. The improved algorithm achieves an optimality gap of 14.9% in 7365 seconds, where Gurobi can only produce solutions with gap of 28.1%.

Modelling Traffic-Distribution based Capacity in the Line Planning Problem for a Railway Junction

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Efficient long-term railway planning necessitates the early integration of infrastructure performance limitations. Traditionally, capacity is estimated first and then used as input for line planning and timetabling. This work presents a novel approach to dynamically incorporate traffic-dependent infrastructure capacity into line planning formulations. We introduce three innovative techniques that model capacity as a nonlinear function rather than a constant upper bound within mixed-integer programming (MIP) formulations. A MIP for calculating minimum headway times at railway junctions is developed, providing input to a queueing system that models timetable capacity based on traffic frequencies and minimum headway times, without needing timetable information—making it particularly effective for strategic planning processes. Our case study demonstrates that all three methods efficiently model capacities in the line planning problem. While the first two methods offer fast computational speeds suitable for scenarios with limited computation time, the third method provides the most accurate capacity approximations. These flexible options equip railway planners to tailor their approach according to specific objectives.

Stochastic Programming for the Line Planning Problem with Uncertain Passenger Demand

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In this paper, we investigate the use of stochastic programming with a recourse action for line planning in public transport systems, specifically addressing the uncertainty in passenger demand. We compare the performance of the integer L-shaped method with a standard solver, focusing on runtime, optimality gaps, and the quality of solutions. Our results indicate that, while the L-shaped method has a large optimality gap and extended runtime, it often achieves similar or even better results compared to the solver and finds good solutions quickly. The analysis of different demand scenarios reveals varying second-stage costs that follow expected patterns. Furthermore, the computed value of stochastic solution (VSS) and the expected value of perfect information (EVPI) are promising, demonstrating the significant benefits of incorporating uncertainty into the line planning process. These findings underscore the importance of developing stochastic models that can effectively handle variability in passenger demand, ultimately improving decision-making and the overall performance of public transport systems.

FRI-5-B: Rescheduling and Traffic Management 3

Time: Friday, 04/Apr/2025: 1:45pm - 3:45pm · *Location:* POT/151/H
Session Chair: Paola Pellegrini

Solving rescheduling problems in heterogeneous urban railway networks using hybrid quantum-classical approach

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We address the applicability of hybrid quantum-classical heuristics for practical railway rescheduling management problems. We build an integer linear model for the given problem and solve it with D-Wave's quantum-classical hybrid solver as well as with CPLEX for comparison. The proposed approach is demonstrated on a real-life heterogeneous urban network in Poland, including both single- and multi-track segments and covers all the requirements posed by the operator of the network. The computational results demonstrate the readiness for application and benefits of quantum-classical hybrid solvers in the realistic railway scenario: they yield acceptable solutions on time, which is a critical requirement in a rescheduling situation. At the same time, the solutions that were obtained were feasible. Moreover, though they are probabilistic (heuristics) they offer a valid alternative by returning a range of possible solutions the dispatcher can choose from. And, most importantly, they outperform classical solvers in some cases.

Integrated optimization of train rescheduling and passenger rerouting with consideration of the rolling-stock circulation

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High-speed railway with its punctuality and reliability, plays an important role in passenger transportation. In the presence of unpredicted passenger demand, dispatchers need to simultaneously reschedule trains and rolling stocks to meet the passenger demand in a short time. This study focuses on the integrated optimization problem of train rescheduling and passenger rerouting with consideration of the rolling stock circulation plan, aiming to solve the problem on three dimensions, i.e., train rescheduling, passenger rerouting, and rolling stock rescheduling. We reconstruct the space-time network by introducing the turnaround arc set, to well represent the limitation of rolling stock circulation, following by an ILP model to formulate the three-dimensional rescheduling problem. The NP-hard problem is then solved by a Lagrangian solution framework, which involves a decomposition approach, a label correcting algorithm, and a heuristic algorithm. We also conduct the experiments on the Beijing-Shanghai high-speed railway line to verify the feasibility, effectiveness, and efficiency of our method, aiming to help dispatchers to make more informed decisions in daily operations.

An integrated deep reinforcement learning and heuristic approach for railway dispatching

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In light of the expected shift of passenger and freight transport to the railway, traffic within railway networks is expected to increase at a rate that cannot be compensated solely through infrastructure development. As the capacity consumption of single network components increases, unavoidable conflicts between train journeys will propagate even further through the network. Currently, classical heuristics are employed for conflict detection and resolution, but they are hampered by relatively long computation times and limited look ahead capabilities. This paper discusses different options to include machine learning components in state-of-the-art heuristics and presents computational tests based on the most promising option. The novel approach demonstrates superiority in terms of solution quality and time when trained on the schedule to be utilized for dispatching. Initial tests on its generalizability to unforeseen schedules applicable within the same network further highlight its potential for broader applications across diverse scenarios

Greedy Randomized Adaptive Search for the real-time Train Routing Selection Problem

Bianca Pascariu, **Paola Pellegrini**
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This paper introduces a novel algorithm for the train routing selection problem (TRSP) within the context of real-time railway traffic management (rtRTMP). The purpose of rtRTMP is to efficiently manage railway traffic in case of unexpected traffic disturbances by retiming, reordering, and rerouting trains. The rtRTMP becomes computationally challenging when numerous route alternatives are available for each train. To address this, the TRSP is employed as a preprocessing step to select the best subset of alternative train routes. These routes are chosen in the TRSP based on estimated costs, which consider the potential train delays that may arise from their use. The selected routes are the only ones used in the subsequent rtRTMP solution. We introduce a greedy randomized adaptive search procedure (GRASP) to select the best subset of train routes in the TRSP. GRASP combines greedy solution construction with randomized search to enhance diversity in the exploration of the solution space. We perform computational experiments, to compare GRASP with the state-of-the-art Ant Colony Optimization (ACO) algorithm for the TRSP. The results show that GRASP outperforms ACO in terms of both TRSP clique quality and rtRTMP objective values.

Adding timetable flexibility to real-time railway traffic management

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The adherence to a timetable with precise departure and arrival times becomes increasingly challenging in real-world scenarios due to the daily fluctuations in rail traffic, leading to uncertainties that complicate effective real-time traffic management. In this paper, we introduce and optimise timetable flexibility to enhance operational robustness and reduce conflicts resulting from minor train path deviations. We propose a Train Rescheduling with Flexibility (TRF) model, relying on a Mixed Integer Linear Programming (MILP) formulation. The primary objective is to minimise timetable deviation, while maximising timetable flexibility. The punctuality threshold is utilised to optimise time allowances within the real-time traffic plan, considering passenger connections and preventing early departures. A real-life case study that focuses on part of the Dutch railway characterised by complex track layouts and heterogeneous rail traffic is used to validate our model. Furthermore, we investigate the impact of predictive delays on flexibility, along with conducting sensitivity analyses on key parameters such as flexibility weight and punctuality threshold. The results of our optimisation model demonstrate its effectiveness in exploiting timetable flexibility to deal with disturbances.

DB InfraGO's Automated Dispatching Assistant ADA-PMB

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As railway infrastructure manager, DB InfraGO AG is faced with the challenge of offering fluid and punctual operation despite rising demand and increased construction activity. The high capacity utilisation, especially in the core network sections, causes delays to be propagated quickly and widely across the entire network. Up to now, conflicts between train runs can be identified automatically, but dispatching measures have been based on past human experience. An automated dispatching assistance system is currently being piloted to provide support for train dispatchers in their work. The aim is to offer them helpful dispatching recommendations, particularly in stressful situations with a high conflict density in the network section under consideration, in order to ensure the most efficient operation of the system. The recommendations are currently displayed separately alongside the central control system. In future, they will be integrated into the central control system, which will significantly simplify communication between the train dispatcher and signal setter. Further development steps for the integration process are also presented and discussed.

FRI-5-C: Train Control and Calibration

Time: Friday, 04/Apr/2025: 1:45pm - 3:45pm · *Location:* POT/251/H
Session Chair: Anders Peterson

A Predictive Artificial Potential Field Method for Virtual Coupling Train Control

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In response to the growing demand for rail transport, next-generation signalling systems are increasingly investigated by the railway community. In particular, the concept of Virtual Coupling (VC) is progressively gaining ground thanks to its potential ability to reduce safe train separation to less than an absolute braking distance allowing trains to move synchronously in a vehicle-to-vehicle radio-connected convoy. One of the major concerns associated with this concept is the safe and effective control of trains in a convoy when considering varying train resistances and risk factors due to, e.g., sudden degradation in the train and communication performance. This paper develops a novel Predictive Artificial Potential Field (PAPF) approach for safe and effective real-time train control under realistic VC operations. The proposed approach uses a realistic homogeneous strip model of train motion and refers to a dynamically changing safety margin to take into account risk factor occurrences such as delays in train control and communication, or sudden emergency braking applications. A simulation-based assessment of the developed method is performed for a high-speed rail corridor in China. Results show that the proposed PAPF control algorithm effectively supervises the safe train separation preventing activation of emergency brakes even when risk events occur. The method contributes to advancing the state of the art on VC train control.

A Reinforcement Learning-Based Adaptive Coupling and Decoupling Control Method for Virtual Coupling Train Sets

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This study first reviews relevant research on virtual coupling and decoupling control, analysing limitations in existing studies and introducing the Reinforcement Learning algorithm using Deep Deterministic Policy Gradient (DDPG) for coupling and decoupling control. Subsequently, the research analyses typical scenarios in the coupling and decoupling process, explaining the process of tracking target transitions and establishing methods for calculating different objective controls within these processes. Following this, a DDPG-based control model that combines offline training with real-time control is proposed. This model considers train nonlinearities and real-world disturbances to develop an accurate train kinematic model. Based on this, state functions, action functions, tracking rewards, and time penalty reward functions are designed within the DDPG framework. Through offline learning, the model optimizes control algorithm parameters for both coupling and decoupling scenarios to meet control requirements in various settings. Then, simulations are conducted on both typical and combined operation scenarios, comparing DDPG-optimized and non-optimized terminal sliding mode (TSM) algorithms. Results show that the DDPG algorithm improves target tracking stability and acceleration stability across coupling and decoupling scenarios. For instance, in combined operation scenario simulations, DDPG achieved improvements of 15.07% in average acceleration, 5.57% in average jerk, 8.41% in tracking distance error, and 8.52% in tracking speed error. Overall, the introduction of the DDPG algorithm results in smoother and more efficient control in both coupling and decoupling scenarios. In the future, this research will further explore issues related to full-scenario control for virtual coupling and heterogeneous multi-vehicle systems.

Trajectory Optimization for Interacting Trains

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Traditionally, timetable and trajectory optimization are handled as separate, sequential steps in both academic literature and planning processes at railway companies. While timetable planning resolves conflicts between all trains, trajectory planning optimizes train dynamics individually. In dense rail traffic, however, the second step can introduce new conflicts, leading to operative intervention of the signaling system with risk of causing delays and energy loss. This paper presents an innovative approach to jointly optimize train trajectories for multiple neighboring trains. Our algorithm iteratively solves a linearized model relating target speeds to passage times for multiple train runs and uses a physics-based runtime calculator to validate new trajectories. Initial results show that complex train interactions can be managed and energy-efficient, conflict-free trajectories are produced that adhere to timetable constraints. The approach promises less signaling interventions, reduced energy consumption and improved network capacity utilization. Future work includes scaling the algorithm for larger networks and extension towards real-time operations.

Calibration of vehicle dynamic and energy parameters of railway vehicles using acceleration sensors

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Simulations, optimizations, energy calculations, digital twins, and other applications require specific vehicle data to describe physical systems. In many cases, approaches for determining this data require much effort and infrastructure data, which are difficult to obtain. The often-required time-space synchronization between measured vehicle and infrastructure data can be a source of error and a challenge. Further, known calibration approaches often depend on the level of detail that describes the vehicle. This paper's contribution is a calibration method and its analyses for railways. The approach requires only data from one acceleration sensor on a regular train run, vehicle masses, speed recording, and power consumption recording. It needs no infrastructure data, such as the line gradient. It can deal with different detailed levels of vehicle modeling. The approach can, for example, simultaneously determine the driving resistance, traction chain efficiency, non-regenerative brake usage, and consumption of the traction power independent consumers. After describing the approach, we compare its applicability with six different levels of detail that describe the vehicle by analyzing the energy exchange, parameters, possible deviation in detail, and numerical stability. The analysis shows that this acceleration sensor-based approach makes it possible to simultaneously determine all mentioned parameters with the data of only 30 minutes of a regular train ride.

Real-Time Mass and Resistance Prediction in Freight Trains Using Adaptive Unscented Kalman Filter

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Accurate estimation of train dynamics, including mass and running resistance, is crucial for improving fuel efficiency, reducing operational costs, and ensuring safe railway operations. In freight trains, mass estimation is particularly challenging due to continuous changes in cargo load and fuel consumption, as well as potential inaccuracies in initial mass estimations. Traditional methods like the Unscented Kalman Filter (UKF) often have difficulty adapting to these rapidly changing conditions, leading to less reliable real-time performance. To address these limitations, this paper introduces the Adaptive Unscented Kalman Filter (AUKF), which dynamically adjusts the process noise, measurement noise, and state covariance matrix to better capture system variations. Using operational data from 74 UK freight train runs, the AUKF delivers more accurate results, reducing the relative Root Mean Square Error (RMSE) of speed by 2.2% compared to the UKF, with an average RMSE of just 0.4%. Furthermore, the AUKF shows greater stability across all runs, providing reliable estimates even when mass fluctuates. This adaptive approach improves the accuracy of real-time predictions for mass and resistance parameters, demonstrating the AUKF's potential to enhance fuel efficiency, optimize real-time control, and increase overall railway operational efficiency.

Usage of train speed data to increase accuracy of running time calculation

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The Swiss Federal Railways (SBB) undertook a revision of planning rules for time reserves in 2018 to address systematic punctuality issues and support the introduction of an automatic Traffic Management System. This led to the recalibration of minimal running time calculations, crucial for timetable construction and dispatching. High-precision speed and distance data, available since 2019, exposed inaccuracies, particularly for freight and long-distance trains. SBB's minimal running time calculation service, ZLR, was refined by integrating track topology, rolling stock parameters, and calculation parameters, significantly improving accuracy.The recalibration targeted modelling the performance of the fastest 10% of train drivers, balancing practicality, simplicity, and computational efficiency. This improved punctuality for local and long-distance trains, although challenges remain for freight trains due to variability. Implemented in the dispatching system in autumn 2022 and set for the 2025 timetable, the new parameters enhance delay management and decision-making, underscoring the importance of data-driven adjustments in railway operations.

FRI-5-D: Planning and Policy

Time: Friday, 04/Apr/2025: 1:45pm - 3:45pm · *Location:* POT/361/H
Session Chair: Alex Wardrop

A Case Study on the Passenger' Travel Characteristics based on Passenger Survey and Railway Tickets Data

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This paper studied the characteristics of passenger travel on the Guangzhou-Shenzhen intercity railway utilizing data from passenger survey questionnaire and ticket sales data. Firstly, 1,380 survey results were collected from the questionnaire in the form of QR code posted at the Guangzhou-Shenzhen intercity railway stations, and preliminary analysis was conducted. Secondly, the K-means clustering method was applied to cluster the passengers of the Intercity Railway, extracting different groups' travel profiles. The passengers were classified into four main profiles, namely business, family visit/holiday return, tourism and vacations, and commuting, with differences in their sensitivity to factors such as travel duration, travel convenience, and train frequency. Thirdly, based on nearly four month long ticket sales data from the Guangzhou Railway Bureau, original-destination passenger flow distribution characteristics and station-to-station train occupancy rate by hour and day were investigated in considering of weekdays, weekends and holidays. The results indicated that passenger flow characteristics had obvious regularity in terms of peakhours,weekdays and holidays; The overall occupancy rate was relatively low and exhibited a significant range of variation. It illustrated that the current train operation plan could not match passenger travel needs well. Finally, with the results of passenger profiles were combining with passenger flow distribution characteristics and train occupancy rate, suggestions for optimizing the operation plan of Guangzhou-Shenzhen Intercity trains were put forward, such as planning train operation on a daily basis with a weekly cycle, optimizing the frequency of train dispatching especially in weekdays and festivals, providing targeted services based on passenger profiles.

Do New Train Stations Drive Economic Activity? Evidence from a 20-Year Analysis in Sweden

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This study investigates the long-term socioeconomic effects of train station investments across Swedish regions, including non-urban and sparsely populated areas, a context often overlooked in transport geography. Using the Difference-in-Differences (DID) estimator developed by Callaway and Sant'Anna (2021), which accounts for variations in treatment effects over time and across locations, we analyze the impact of 44 train station openings between 1995 and 2015 on population and income. Compared to areas without stations, the treated group experienced a 13.2% increase in total population, a 14.8% growth in the working-age population, and a 15.2% rise in total earned income over 20 years. However, no statistically significant changes in per capita income were observed. This suggests that while the train stations attracted population growth and raised overall income, they did not increase average income levels relative to control areas. The impact was stronger in areas with initially lower incomes, where total income and the working-age population more than doubled compared to higher-income areas. These findings challenge the conventional rationale for railway investments—improving accessibility and stimulating economic growth—and highlight the importance of context-sensitive infrastructure policies.

Double Deck vs Single Deck Suburban Trains

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In Australia there have been continuing discussions about the merits of double deck and single deck cars for use in suburban passenger train service. This discussion has usually centred around the merits of having two or three sets of double doors down the car sides and what impact this might have on station dwell times. However, there has been scant discussion on what the suburban passenger service duty cycle might be, since this should be the more important determinant of station dwell times. This paper thus attempts to integrate the characteristics of suburban passenger operations, the incidence of heavy lift stations, passenger flows, the access/egress performance of different car designs, likely outturn station dwell times and the headway characteristics of alternative signalling designs into an operational design model. Interpretation of modelling results across a range of car designs then points to where double deck and single deck car designs perform best.

Obtaining a fit-for-purpose train planning process for a sustainable railway: Perspectives from Great Britain and Germany

Nadia Hoodbhoy[1], Gemma Nicholson[2], Heather Steele[2], Irene Sturm[3], Andreas Söhlke[3]

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The ongoing and planned rollouts of the European Train Control System, known process weaknesses and high demand for capacity and performance present the necessary conditions for an overhaul of the train planning lifecycle. This paper discusses efforts to redesign the train planning process by Network Rail and Deutsche Bahn, driven by their planned digitalisation. To be fit-for-purpose, train planning must support improved flexibility and risk management whilst delivering a feasible timetable, optimised against capability goals. To deliver this requires a business level decision to adapt or transition away from embedded toolsets and management practices, which involves risk and expense. Market surveys by both Infrastructure Managers concluded that there is no single tool that can meet all the requirements of supporting a redesigned, integrated train planning process. Supplier feedback indicates that the development of changed functionality must be industry-led and requires a huge resource commitment and expertise. Whilst Network Rail is expecting to undertake collaborative development in innovation partnerships with suppliers, Deutsche Bahn is developing traffic management and timetabling systems (and associated AI expertise) in-house. A gap in the adoption of academic research into commercial toolsets is identified which requires a focussed effort on bridging the gap collaboratively by multiple stakeholders.

Identifying Risk Factors and Improving Rail Safety By Using Logistic Regression and Ensemble Learning Approaches

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Train derailments pose significant risks to safety, infrastructure, and the environment. Understanding the factors that contribute to these incidents is crucial for developing effective prevention and mitigation strategies. This study employs logistic regression to investigate the predictors of train derailments using the accident dataset from the Federal Railroad Administration (FRA). The model identified track type and presence of engineers as significant factors influencing derailment risk. Yard tracks, industry tracks and sidings were found to have higher odds of derailments compared to main tracks, emphasizing the need for targeted safety measures in these areas. Also, the presence of engineers was associated with reduced derailment odds, highlighting the importance of skilled crew in ensuring safe operations. This study also employs adaptive boosting, an ensemble learning technique to predict derailment accidents. The model accurately predicts 72% of all instances of derailment and non-derailment accidents. The learning model also identifies the gross tonnage of the train as a key factor in predicting the likelihood of the train derailing. These findings provide valuable insights for developing evidence-based interventions by railroad authorities and safety agencies to mitigate derailment risks and enhance rail

Poster Session

Wednesday, 2nd April

WED-3-A: BREAK + POSTER SESSION

Time: Wednesday, 02/Apr/2025: 11:00am - 12:00pm · *Location:* POT/168/S

Optimal Strategy Estimation for Real-time Traffic Management: An Optimization-learning Framework-Based Method

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Train dispatching strategies are essential for effective real-time traffic management. This paper proposes an innovative optimal strategy estimation method based on optimization-learning framework, designed to identify the best-chosen strategies under different perturbance scenarios to give decision-support to the dispatchers. This framework consists of two layers: the optimization layer and the learning layer. In the optimization layer, a mixed integer programming model is developed, incorporating eight different dispatching strategy sets to determine optimal strategies and their recommended probabilities for a range of pre-defined perturbance scenarios. The results from this layer serve as inputs for the learning layer. The learning layer employs a deep learning model based on a Multilayer Perceptron to train and learn the mapping relationship between different perturbation scenarios and the recommended optimal strategies. The optimal chosen strategy sets under real-time perturbances will be used as outputs to support dispatching decision-making. To validate the effectiveness and accuracy of the presented approach, numerical experiments based on real-world data are from Beijing-Shanghai high-speed railway line are conducted. The experiments results demonstrate that the proposed optimization-learning approach can achieve 91.3% accuracy in predicting the most recommended optimal strategy set under disruption scenarios, and 67.6% accuracy in predicting the success of all eight strategy sets in the recommendation sequence.

Modelling the Interactions between Heavy Axle Weight Rail Freight Traffic and Underbridges

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Faced with a combination of ageing infrastructure, changing traffic patterns, climate change impacts and the need for modal shift to rail, freight train operators and railway infrastructure managers need improved methods and tools for the planning and management of freight train paths and infrastructure maintenance, renewals and enhancement. Since underbridges tend to be the limiting factor for the accommodation of heavy axle weight freight traffic, they require particular attention. In order to meet these needs, new methods and an integrated tool were developed to visualise the railway network and its assets, and to model the routeing of freight services and the degradation of underbridges, the interactions between traffic and the bridges, and the impacts and constraints they impose on each other. The integrated modelling tool combines data from a range of sources in an online geospatial database, making use of industry standard, open-source techniques and tools, and thus maximising reliability and deployment flexibility and the scope for further expansion of the system. The database interacts with bespoke structural degradation modelling tools to determine the impacts of traffic on bridges and vice versa. Work is continuing to extend the model's coverage from an initial exemplar route to Britain's full national railway network, and the possibility of expanding its coverage to include additional infrastructure asset categories is being considered.

A deep reinforcement learning approach for rolling stock circulation on urban rail transit line

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Rolling stock circulation involves assigning rolling stocks to a predetermined set of train trips with fixed departure and arrival times. This paper addresses the mathematical modeling, solution methods, and numerical experiments for both hypothetical and real-world cases of rolling stock circulation, specifically considering two endpoint depots on an urban rail transit line. Multiple objectives are considered, including minimizing the total number of rolling stocks in utilization, balancing the workload among the utilized rolling stocks, and ensuring the inventory equilibrium at each depot at the start and end of the planning horizon. To achieve these goals, we propose a multi-commodity flow model and a deep reinforcement learning (DRL) framework for the rolling stock circulation problem. The multi-commodity flow model is formulated as a non-linear integer programming problem, accounting for multiple types of rolling stocks. The commercial solver and a custom-developed ant colony optimization algorithm are applied to solve the model, serving as benchmarks for comparison. The rolling stock circulation problem is innovatively modeled as a Markov decision process within an advanced single-agent learning environment, that integrates state definition, constraint detection, and reward assignment. In the deep reinforcement learning framework, a proximal policy optimization algorithm is employed to solve the proposed problem efficiently. Numerical experiments on hypothesized and real-world cases illustrate the effectiveness of the proposed deep reinforcement learning method for rolling stock circulation, showing superior solving quality and efficiency compared to benchmark approaches. Furthermore, generalization tests prove the method's strong potential to handle problems of various scales efficiently.

A Dynamic Model for Train Scheduling and Resource Allocation in Urban Rail Transit Systems

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Mobility as a Service (MaaS) integrates various transport modes into an on-demand and real-time platform, providing dynamic door-to-door services. Within the MaaS platform, travel demand is volatile and dynamic, and passengers have more flexibility in bookings and cancellations. More than ever, rail operators have to be agile and adaptive while making operational decisions. We propose a dynamic model to help rail operators make adaptive train scheduling decisions based on stochastically evolving bookings and platform signals. By leveraging emerging virtual coupling train platooning, the model facilitates flexible resource allocation to trains, preventing over-congestion at rail stations due to high passenger volumes. It incorporates both train arrivals and departures for new bookings and cancellations, as well as platform information that affects future demand. This significantly generalizes and strengthens previous modeling attempts. We analyze the mathematical properties of our formulation and develop a Benders-based branch-and-cut (BBC) algorithm that decomposes the dynamic program into separable train-level problems. In our BBC algorithm, we derive two sets of time-related valid inequalities to improve the tightness of the master problem, which can be generalized to address a broad class of time-indexed formulations. For the subproblems in the BBC, we establish optimality conditions and demonstrate that these subproblems can be solved analytically. Our analysis provides new theoretical, algorithmic, and managerial insights into dynamic train scheduling and resource allocation. Real-world case studies based on practical urban rail transit data demonstrate the potential benefits of this approach.

A heuristic framework for pod scheduling with empty carrier movement

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Amid the growing need for more sustainable freight transport, the rail sector faces challenges in competing with road transport due to lower flexibility and reliability. To address these challenges, intermodal rail freight systems must evolve to enhance flexibility and integrate more seamlessly with broader mobility services. A key factor in the success of such innovations is the integration with existing railway infrastructure. This study examines the concept of modular vehicles (MVs) in rail systems, focusing on the innovative 'Pod' system developed in the Pods4Rail project. These Pods consist of detachable flat wagons (carriers) and capsules or containers (transport units) capable of moving both goods and passengers. A fundamental requirement for MVs is the assignment of carriers to transport units, allowing them to operate on the rail network. This involves , ensuring the availability of carriers at pickup points in terms of assignments of carriers to transport units as well as relocating empty carriers across the network. This may lead to empty runs and potential capacity challenges. Once assigned, complete Pod formation (combinations of carriers and transport units) form swarms or platoons through virtual coupling, which could significantly improve capacity utilization. This paper presents a heuristic framework that incorporates the assignment of carriers to transport units, and pod dispatching for pickup and delivery, including empty carrier circulation, considering parameters for the operation in virtual coupling. Results indicate that platooning reduces makespan for larger problem sizes, but requires a sufficient number of carriers.

Capacity analysis for railway infrastructure nodes using periodic timetabling

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Railway capacity assessment plays a crucial role in boosting railway network efficiency by identifying bottlenecks and guiding strategic decisions. However, evaluating railway capacity is a challenging task due to its dependency on various critical components of the railway system, including infrastructure, rolling stock, signaling system, and service planning. This paper addresses the problem of analyzing the capacity of railway nodes, such as stations and junctions, which are often identified as network bottlenecks. In particular, it introduces a novel mixed-integer linear programming (MILP) model aimed at assessing capacity when periodic timetables are aimed at a node. The model assesses whether, or to what extent, a node can host ideal or regular timetables expressed in terms of service frequencies within a specific time frame, while allowing for some deviations from a perfect periodic schedule. The assessment is possible both when using a fixed, predetermined route for each service, and when exploiting rerouting options. The model is built upon the MILP formulation at the basis of RECIFE-MILP, a proven, high-performance tool for real-time railway traffic management. It utilizes RECIFE-MILP's realistic microscopic infrastructure representation, including the route-lock sectional-release interlocking system, which is essential for accurately capturing operational constraints limiting capacity. Additionally, periodic timetabling constraints are incorporated to ensure that train services are scheduled at regular intervals, establishing a repeating cycle in the timetable. To determine maximum capacity, we employ an iterative process that incrementally increases demand until the model proves the impossibility to schedule additional trains. Our experimental study, conducted on different French nodes, demonstrates the model's ability to provide capacity analysis insights by considering both homogeneous and heterogeneous traffic scenarios. Moreover, the study allows the quantification of the impact of rerouting options on capacity, thus opening the way to the analysis of different infrastructure layouts.

Design Automation for Modern Train Control Systems

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Railway transportation will play a vital role in future sustainable transportation. Yet, planning of new railway infrastructure is mainly done by hand. Our work focuses on automation methods to aid in designing optimal signaling systems on new and existing tracks. Classically, trains are separated by fixed blocks, and Trackside Train Detection (TTD) hardware (e.g., axle counters) is used to identify whether a specific block section is free. At the same time, modern train control systems allow trains equipped with integrity monitoring to safely report their exact position without the need for TTD hardware. This allows separation into smaller (purely virtual) subsections, enabling shorter headway times. However, the question arises of where these virtual subsections should be placed to allow for the best operational outcome (e.g., measured by minimizing travel times or maximizing capacity). To the best of our knowledge, only limited research includes these operational objectives already at the infrastructure planning stage. First design automation methods to tackle these problems have been developed based on SAT, A*, and Integer Programming and implemented open-source (available on GitHub at https://github.com/cda-tum/mtct). These models contain a decent amount of variable decisions such as train routing, timing, and block layout generation, each of which is already hard on its own. Hence, existing methods do not yet scale well to real-world-sized instances. Our future research aims to overcome this issue with a sensible optimization pipeline and tailored algorithms. All resulting methods are integrated into the open-source Munich Train Control Toolkit and available to the public.

Capacity Analysis of Thailand's Southern Railway Corridor: Enhancing ASEAN Rail Freight Cross-border

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Southeast Asia's economic growth has heightened the importance of international rail transportation, especially within the framework of the Singapore-Kunming Rail Link (SKRL) and the ASEAN Express initiative. These collaborative projects emphasize the development of interconnected rail networks. The Thailand-Malaysia railway corridor represents a historically significant cross-border connection with a long tradition of continuous operations. Although the two countries now have different levels of rail system development, cross-border freight transportation remains active between them. However, the increasing trend in international freight train volumes poses a potential challenge to both domestic passenger and freight services, which necessitates a systematic study and evaluation of the line capacity. The purpose of this research is to evaluate the capacity of Thailand's Southern railway corridor through application of the UIC406 compression method. The analysis reveals two critical bottlenecks: (1) the single-track segment between Chumphon and Padang Besar, and (2) Bang Sue Junction, which experiences high-density freight traffic. The study proposes route management strategies to accommodate increasing train volumes, which will directly contribute to the development planning of Thailand's rail transport system. These findings provide guidelines for enhancing cross-border freight transport capacity along the Malaysia-Thailand-Laos-China railway corridor in the future. This development will play a crucial role in promoting regional economic growth and aligning with ASEAN's vision for enhanced rail connectivity.

Computer Vision for Drone Inspection of Railway Assets: the RADIUS case study

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The inspection of railway assets is a critical task for ensuring the safety and reliability of railway networks. Traditional methods often require manual, time-intensive processes that may pose risks to personnel and disrupt operations. Recently, advances in drone technology and computer vision are suggesting an opportunity to revolutionize this field, disclosing the possibility to efficiently monitor and analyse the condition of railway infrastructure, detecting faults and irregularities without the need for frequent human intervention. The European project "Railway digitalisation using drones" (RADIUS) investigates the use of drones to execute the inspection of different assets. In particular, this poster focuses on the development and application of computer vision techniques for drone-based inspection of switches, cabinets, light signals, and level crossings. The key algorithms employed are based on Convolutional Neural Networks (CNNs) – a leading class of deep learning models for computer vision tasks – and, in particular, the developed solutions leverage transfer learning, i.e., the idea of exploiting pre-trained models and adapt them on new, but related, tasks. This approach leverages the knowledge learned from a larger dataset to improve performance on smaller task-specific datasets like the ones we deal with in the project. The methodology was tailored to the unique challenges of drone-based inspection, accounting for real-world variables such as drone positioning and atmospheric conditions. Indeed, the implemented models follow a pipeline designed to (i) accurately identify railway assets in images, even in the presence of noise, and (ii) detect anomalies with respect to the expected normal conditions. The results, derived from drone-captured images of the Portuguese railway infrastructure, demonstrate the feasibility and effectiveness of these solutions in real-world environments.

Efficient Flat Yard Shunting via Instance-Aware Optimization

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The process of switching cargo wagons, known as shunting, is a major challenge in railway operations. Faster shunting operations would simultaneously increase the profitability and attractiveness of rail-based cargo services, thereby positively impacting transport sustainability. We recently proposed a metaheuristic called HEROS (Hybrid of Evolutionary and Reinforcement Optimization for Shunting), which is explicitly designed to optimize shunting time in flat yards. It employs multiple concepts from evolutionary computation and reinforcement learning. Moreover, we designed the algorithm to be highly configurable so that it can be adapted to different problem instances, i.e., yard layouts with different combinations of wagons and tracks. Initial experiments indicate that the algorithm's performance is highly sensitive to the hyperparameter configuration. In this work, we examine and exploit the adaptivity of HEROS to ensure its efficiency for various shunting scenarios. For this purpose, we first conduct an extensive benchmark study, in which we investigate the effects of different hyperparameter configurations of HEROS on its performance. As a basis for the benchmark study, we first generate multiple shunting scenarios, by varying the number of wagons and tracks, as well as the order of wagons per track, and then measure the performance of various HEROS configurations per scenario. We will then determine optimal hyperparameter configurations for specific shunting yard scenarios based on the resulting experimental data. At last, we seek to improve the current version of HEROS by implementing an instance-aware automated algorithm configuration approach that sets the hyperparameters based on the identified patterns. By introducing this automated process, we expect to increase both the efficiency and usability of HEROS, making it more attractive to a broader user group while at the same time providing a substantial performance improvement over the current state of the art.

Sustainable Periodic Timetabling for Railways

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To reach climate goals, it is desirable to design an environmentally friendly transport system. On the one hand, as many passengers as possible should be attracted to use public transportation. Hence, short travel times, and in particular short transfer times, should be achieved. On the other hand, the public transport system itself consumes a non-negligible amount of energy. A way to reduce this amount of energy is the usage of modern electric motors which are able to regenerate energy while braking. In the context of rail traffic, the most efficient way to use the regained energy is to transfer it via the catenary to an accelerating train close by. This poster presents a MIP model based on the PESP that aims at optimizing the usage of regenerative energy. Assigning arrival and departure times, the model also decides between which pairs of trains a transfer of energy takes place and it maximizes the total brake traction overlap. In addition, the objective of minimizing the passengers' travel time is considered. While the usage of regenerative energy profits from synchronized brake and traction phases of two trains, such a timetable prevents the transfer of passengers from the braking to the accelerating train. A study investigating the trade-off between energy and transfer time optimization at one transfer station is conducted. Structural properties of Pareto-optimal timetables are presented and the problem's complexity is analyzed for some special cases. These results were published by Jäger et al. (2024).

References

Sven Jäger, Sarah Roth, and Anita Schöbel, 2024. "Periodic Timetabling: Travel Time vs. Regenerative Energy", In: 24th Symposium on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2024). Open Access Series in Informatics (OASIcs), Volume 123, pp. 10:1-10:20, Schloss Dagstuhl – Leibniz-Zentrum für Informatik (2024)

Enhancing the reserve capacity of an urban rail transit network by adding rapid transit lines

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The reserve capacity of an urban rail transit network (URTN) is crucial for mitigating the impact of potential service disruptions. In this paper, we present a novel tool to enhance URTN reserve capacity by designing new rapid lines that connect suburban areas to the metropolitan city center. Mathematically, the problem is formulated as a three-level integer program: the upper-level subprogram maximizes the total number of origin-destination (O-D) pairs that the network can serve, the middle-level subprogram determines service plans for the new rapid lines, and the lower-level subprogram calculates the maximum passenger flow between each O-D pair under the optimized service network. Computationally, an Adaptive Large Neighborhood Search (ALNS)-based nested iteration algorithm is applied to solve the model. Numerical examples demonstrate the effectiveness, features, and adaptability of the model and algorithm in optimizing network reserve capacity. The results indicate that optimizing service lines within the URTN can increase the utilization of the network's physical capacity. Moreover, the distribution structure of passenger flow demand significantly affects the network's maximum reserve capacity. This research on reserve capacity offers practical operational guidance for designers and operators of service lines, aimed at enhancing the resilience and efficiency of urban rail systems.

Forecasting Railway Network Resilience under Propagating Uncertainty

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The resilience of railway networks in the face of weather-related disruptions is a critical concern, particularly with the increasing frequency of extreme weather events. Local failures not only cause direct impacts but also propagate across the network, amplifying uncertainty and increasing risks to journey connectivity, as well as the flow of passengers and goods. This study addresses the challenge of forecasting network resilience under the propagating uncertainty caused by weather conditions and asset failures. To tackle this, we developed a computational model that quantifies the resilience of the railway network in the UK by calculating incident probabilities and simulating the propagation of uncertainties arising from weather events and asset vulnerabilities. The model utilises historical weather data and disruption records to estimate the failure probability of key railway assets such as rail tracks, overhead lines and lineside vegetation. It combines regression analysis with a Bayesian inference framework to conduct probabilistic assessments and generate a risk map that visualises how local failures impact broader network performance. This map, alongside a software tool, will be deployed on the UK's DAFNI (Data & Analytics Facility for National Infrastructure) platform to provide railway operators with better-informed decision-support tools for routing, scheduling and alternative service provision during disruptions. The study provides short-term predictive capabilities, offering insights into potential disruptions within a specific timeframe (e.g. hours, days or up to two weeks) in advance. By leveraging data sharing and integration, adhering to FAIR (Findability, Accessibility, Interoperability and Reusability) principles, and employing advanced data analytics, the modelling tool and comprehensive risk map will enhance the understanding of operational resilience and support strategic planning for a more reliable and adaptable railway network. Ultimately, the study contributes to safeguarding transport networks against the growing challenges posed by climate change, improving the reliability and accessibility of railway services across the UK.

Optimizing Railway Operations with Track Predictive Maintenance Strategy

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Ensuring safe and efficient train operations require effective monitoring of both train and infrastructure. Having a precise method for detecting the health of infrastructure has a great impact on the operation side. This study focuses on monitoring Track Geometry to detect irregularities and enable infrastructure managers to implement a predictive maintenance strategy. This should provides from an operational perspective, significant benefits as: reducing the need for unplanned maintenance to minimize train delays, ensures consistent train speeds, and improves punctuality. Furthermore, this research aims to remove diagnostic trains and use on-board sensors installed on commercial trains which would enhances line capacity, enabling more trains to operate efficiently without compromising safety and interrupting the traffic. The precise data also helps optimize maintenance schedules, reducing unnecessary interventions and cutting costs. The methodology involves the use of an onboard sensor system installed on commercial trains. A stereo camera mounted at the bottom of the bogie captures real-time images to measure Lateral displacement of the wheel in relation to the rail, while thermal camera could also monitor the temperature of the rail and wheel to detect anomalies related to wheel-rail interaction. The collected data is stored to the clouds and eventually could be transmitted to the control center, enabling real-time monitoring, temporal evolution analysis, and long-term assessment of the track's structural health by use of Machine Learning models. In conclusion, this research highlights the potential of onboard sensor systems and advanced data analysis to improve track maintenance strategies with effects on the operation side.

How Can a Self-Learning Tool Support Knowledge Transfer in Railway Operation Laboratory?

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The Railway Operations Laboratory at Dresden University of Technology demonstrates various generations of signaling systems, from the earliest mechanical techniques to the latest digital technologies, enabling the integration of diverse technical components in unified simulation scenarios. This hands-on facility offers practical lab experiences for students in traffic engineering and railway systems engineering, attracting substantial interest due to the interactive railway model systems that students can directly observe and operate. The laboratory currently operates seven distinct stations, each requiring dedicated instructors for training across different signaling systems, thus demanding significant instructional resources. This study aims to develop a self-learning environment to optimize instructional workload and enhance knowledge transfer. The focus is on creating a web-based learning program that enables students to practice and perform operational tasks autonomously at a pilot station under regular train operational conditions, with scalability for future application to other stations. The research begins with an analysis of current instructional and simulation practices at the pilot station, assessing software and system requirements. The learning environment is designed progressively, from Low-Fidelity wireframes to High-Fidelity prototypes using Figma, a powerful, collaborative design tool, that allows students to engage in structured, interactive tasks of increasing complexity. The resulting self-learning environment provides a comprehensive platform for independent practice, reducing reliance on direct instruction. This design accommodates training from regular operations to complex scenarios, and is adaptable for both disruptions and deviations from regular operating conditions.

How to divide the rolling stock over the shunting yards: what makes a shunting yard instance solvable?

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In the off-hours of passenger railway traffic, trains need to be routed to shunt yards located near major stations, where they are parked, cleaned, checked, etc. For routing the trains from the station to the shunt yard and back a schedule must be made that ensures that no train is in conflict with another, or with other through traffic. On the shunt yard itself, a schedule must be made by solving the Train Unit Shunting Problem with Service Scheduling (TUSPwSS). When a station has multiple yards located nearby, trains need to be distributed such that each yard has enough capacity to park and service the trains. Unfortunately, it is not clear beforehand whether an instance of TUSPwSS is feasible. To investigate this, we have analyzed a number of factors that play a role in the capacity of a shunting yard. On the basis of these results, we have built a logistic regression model for each yard to determine if an instance is solvable by the current TUSPwSS solver in reasonable time. In an earlier stage we have built a constraint program (CP) based on a node-packing formulation that can be used to solve the problem of routing trains from the station area to the shunting yards. To this CP we add an objective that optimizes the probability of solving the resulting TUSPwSS instances based on the logistic regression models. This guides the search towards solutions that have a high probability of succeeding in both the station area and shunt yards.

Impact Assessment of railway systems to increase attractiveness

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The research addresses the deployment of new systems that can enhance railway operational capacity and efficiency. The research introduces a framework to support the analysis and strategic development of railway systems. It applies interdisciplinary approaches to complex decision-making, including market potential assessment, decision-making, and scenario-based roadmapping. The analysis was showcased for Moving Block (MB) and Virtual Coupling (VC) railway signalling technologies and is developed further for application to other systems. The developed framework provides a coherent and holistic architecture within the development and evolution of systems where step-changes can be explored, mapped and interpreted based on distinct scenarios and specific project context. It can also foster business growth and organizational changes. The study evaluates the railway system's attractiveness across railway segments. The goal is to promote a shift from other transport modes to rail, ultimately leading to reduced road traffic congestion and CO2 emissions. Further, a Multi-Criteria Analysis (MCA) offers a comparison among alternatives across multiple criteria like cost, capacity, energy consumption, and regulatory approval. Findings reveal that the integration of SWOT, MCA, expert judgement, gap analysis and scenarios within the framework provides a means for addressing corporate challenges and exploring new application opportunities, even in low-developing countries. Finally, the study provides a detailed roadmap, showing how the implementation of railway systems can maintain efficient operation even under degraded conditions. This comprehensive study equips railway practitioners with strategic planning tools and implementation roadmaps for deploying new railway systems and advancing rail technology amidst growing railway demand.

Impact of a summer drought on ground deformations near railways: exploring the summer of 2018 in Southern Sweden

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The summer of 2018 in Sweden can be described as one of the hottest and driest recorded, especially affecting southern Sweden. On the short term, the southern main line, a railway line connecting Stockholm with southern Scania, suffered lower punctuality at many locations related to weather events. However, the low precipitation may have a longer-term effect on the rail positions, as the soil stability is affected by the dry period. This research aims to understand the effect of dry periods on railway substructure, using an especially dry and hot summer of 2018 and southeastern Sweden as a case study. The research considers three stations with similar traffic conditions along the southern Main Line of Sweden during the summer of 2018: Alvesta, Nässjö C, and Linköpings C. Precipitation levels were assessed using the Standardized Precipitation Index (SPI) for 30- and 90-day precipitation totals. Similarly, the vertical and horizontal deformations, retrieved from Interferometric Synthetic Aperture Radar (InSAR) data, were analyzed as 30- and 90-day deformation velocities. The precipitation index and the deformation velocity were analyzed jointly. The results are expected to reveal differences in ground motion velocity for different precipitation scenarios on a semi-short term of one to three months. It is expected that periods with higher-than-normal precipitation will show a higher negative vertical velocity compared to periods with drought. Further, from previous literature, it is expected that wet periods preceded by a drought will have higher negative velocities compared to wet periods that occur after relatively normal precipitation amounts.

Integrated crew management for rail freight

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The construction of yearly schedules for train drivers is a challenging problem in the railway industry. Generally, the planning process is addressed sequentially: first---the Crew Scheduling---, driving tasks (assumed to be identical every week) are combined together to form daily duties; then---the Crew Rostering---, these duties are organised together in rosters, providing the yearly schedules. A common variation of the latter, the Cyclic Crew Rostering, is used at Fret SNCF (the main French railway company's freight subsidiary), but also in other countries (Breugem, Dollevoet and Huisman). For this variant, the drivers are first split into teams. Then the cyclic roster of each team is obtained by cyclically rolling out the weekly schedule of each driver, provide their yearly schedule. Such rosters are easy to memorize, they ensure fairness between drivers and stable proficiency levels. The decomposition of the planning process into Crew Scheduling and Rostering is justified by numerous operational rules, along with the combinatorial complexity of both problems. However, this decomposition results in sub-optimal solutions. Lin and Tsai propose to solve the integrated version via column generation. Fret SNCF faces additional challenges making their approach irrelevant: some trains are driven at night (passenger has priority over freight in France), preventing a day-to-duty matching in rosters, and the objective function is not linear in the duties. We propose a column generation approach to the integrated Crew Scheduling and Cyclic Crew Rostering, in which columns are not rosters but ``long shifts,'' representing the working period between two days off, making the objective function linear. A non-trivial contribution is the modeling of the pricing sub-problem as a Resource Constrained Shortest Path Problem, within the setting of Parmentier. Our approach already provides an optimal solution to an instance of 265 trains, gaining 10% against the cost achieved by the sequential approach.

Integrated Train Timetabling and Rolling Stock Circulation Planning for a Metro Line with Storage Tracks: A Flexible Train Composition Mode

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The uneven distribution of passenger demand in both space and time presents a prominent challenge in metro operations. To better meet the passenger demand, this study focuses on optimizing the coordination of train timetables and rolling stock circulation plans. A novel approach is proposed through a flexible train composition mode, which allows rolling stock to adjust their composition at predefined intermediate stations with coupling/decoupling capability. Disassembled train units can be stored on the corresponding storage tracks of these stations, where the train units may later be coupled with other rolling stocks. The optimization problem is formulated as a mixed integer nonlinear programming (MINLP) model that simultaneously optimizes the train timetables, rolling stock circulation plans and coupling strategies, with the objective of minimizing the total number of train units required, the total running distance of train units and the total waiting time for passengers. A set of binary decision variables is introduced to represent the flexible train composition status and storage capacity of train units at each predefined intermediate station. To improve the model's tractability, it is reconstructed into a mixed integer linear programming model (MILP) using a linearization method, and efficiently solved with the MILP solver CPLEX. Moreover, a customized heuristic algorithm based on adaptive large neighborhood search (ALNS) is developed to generate high-quality solutions. Two sets of numerical experiments are conducted to validate the effectiveness and applicability of the proposed method, using both a small example and data from Shanghai Metro Line 16. The results indicate that, for the small example, the proposed model improves the objective value by 37.3% with a minimal increase in passenger waiting time. For the large-scale examples, the proposed algorithm enhances the objective value by 6.7% after 500 iterations, though the ALNS-based solution still offers potential for further improvement.

Research on Collaborative Optimization of High-Speed Railway Revenue in a Market Competitive Environment Based on Spatiotemporal Service Network

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High-speed railway (HSR) transport has become one of the primary modes of travel across Asia. However, from the perspective of the transportation market, HSR passenger services face multi-faceted competition, including from the aviation industry. As consumers, passengers also consider various factors and personal needs when choosing their mode of travel. In fact, the aviation industry, through revenue management strategies such as fare discounts and seat allocation, has successfully attracted passengers and expanded its market share. To enhance their competitiveness, HSR companies must adopt differentiated pricing strategies. In this study, all origin-destination (OD) pairs within a transportation corridor during a given period are considered, and a competitive market environment is created by accounting for all trains and flights operating within that corridor. To model passenger travel behavior, the study introduces constraints reflecting the fully rational, compromise-based decision-making process of pass

Night train to Lisbon: An analytic approach to Pascal Mercier's philosophical novel

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Pascal Mercier's novel Night Train to Lisbon is, among other things, about a night train journey from France to Portugal. As these services have been suspended, such a journey would no longer be possible. An overnight train to Lisbon thus provides a realistic research framework for the question of how such an offer could look like based on objective criteria. For this purpose, a heuristic is presented that considers demand potentials and eventually allows a derivation of origin-destination matrices. The derivation of potentials on which the calculations are based are explained in detail. By means of the defined geographical area of a night train service in Portugal, Spain and France, the application of the NUTS classification is also tested that could be extended to cover wider areas. Finally, a night train service to Lisbon can be created, that can be compared with actual historic night train services. These are presented for timetable 2021 and allow an insight into the night train market on the Iberian Peninsula.

Combination of Simulation and Optimization of Freight Railroad Vertical Alignment to Maximize Diesel Saving Benefits of Battery Electric Locomotives (BELs)

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In an effort to decarbonize, heavy haul freight railroads are exploring alternative energy technologies such as the Battery Electric Locomotive (BEL). A BEL produces tractive effort from electricity stored in onboard batteries that are re-charged at terminals and/or through regenerative braking. Because they can leverage braking energy, the performance, range, and diesel fuel savings of BELs are expected to vary with route topography, train weight, balance of loaded and empty traffic by direction, and battery storage capacity. These complexities raise the research question of where BEL deployment will offer the greatest benefits. To identify routes that maximize BEL decarbonization benefits, a combined simulation and optimization approach was developed. First, a systematic set of short route segments encompassing different vertical gradients and representative BEL deployment conditions is created. Using validated models of freight train, diesel-electric and battery locomotive performance, the energy consumption, regeneration and diesel fuel savings obtained by substituting a BEL for a conventional diesel-electric locomotive across each short route segment is simulated with the Advanced Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS). Next, based on this set of simulation results, a Mixed Integer Linear Program (MILP) is constructed to identify the set of vertical grade segments that, subject to appropriate constraints, maximize diesel fuel savings from deployment of a given size BEL on a corridor with a specified length and traffic distribution. The results support initial hypotheses regarding the research problem, and these findings provide a foundation for future research to identify optimum routes in larger freight networks.

A Practical Approach to Train Timetable Optimization: Incorporating Bottleneck Operations and Practical Start Times

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In the train timetable optimization problem, some operations may experience substantial delays, often due to train sequencing or operational uncertainties. As a result, real-time timetable optimization can sometimes lead to impractical plans. To derive a more applicable and realistic solution, we focus on avoiding the optimization of operations with significant delays, which we identify as bottlenecks. By treating practical timetables as historical records of train movements, we use passenger and freight demand to predict practical start times through an Artificial Neural Network (ANN). These start times are then used to develop a more realistic train timetable solution. Using disjunctive linear programming, we ensure that the start time of each bottleneck operation is at least as long as the practical duration of its preceding operation, while other operations are optimized accordingly. By allowing for the fluctuation of bottlenecks within the timetable, we create a more reliable and realistic schedule that remains close to the optimized solution, thus supporting real-life and real-time train timetabling. In testing on a sample network, the proposed method's average total timetable is 179.7 units higher than the optimized solution and 16.8 units lower than the practical values. Furthermore, the variance of fluctuating operations is significantly reduced, indicating a more practical and applicable solution for operators.

Dynamic Pricing Strategy for High-Speed Railway During the Pre-sale Period through Passenger Flow Assignment Analysis

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The study took the high-speed railway under the condition of network as the research object, analyzed the overall idea and adjustment strategy of pre-sale dynamic pricing optimization for high-speed railway. Based on the three-dimensional space-time service network, considering economy, rapidity, convenience and comfort, the research proposed the generalized cost formula of reasonable service routes, established a multi-objective dynamic pricing model, presented the multi-dimensional fare adjustment strategy, designed dynamic pricing algorithm based on the fare adjustment strategy-passenger flow assignment. Through the case of Beijing-Shanghai high-speed railway, the total revenue, pre-sale period fare fluctuation and passenger flow assignment result were analyzed. The results showed that under the different price gap and same fare adjustment strategy, the total revenue increased significantly when fare fluctuated. Under the same price gap and different fare adjustment strategy, the revenue curve showed an obvious inflection point when the fare rate increased by 15% and the slope of the revenue curve was almost zero when the fare rate increased by 20%. And the average passenger load factor of trains could be increased by 5.9%. In summary, the case of Beijing-Shanghai high-speed railway verified the feasibility of above model and algorithm and the effectiveness of the multi-dimensional fare adjustment strategy.

Research on Optimization of Air-rail Intermodal Transportation Network Considering Channel Capacity Constraint

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Air-rail integration is an integral component of intermodal passenger transportation in China. The collaboration between high-speed railway and civil aviation facilitates mutual complementarity and mutually beneficial development, enhancing the coverage, efficiency, and societal benefits of transportation networks to better meet diverse passenger travel demands. However, there are certain disparities in resource allocation and advantageous route distances between aviation and railways in different regions, which can be fully utilized in the design of intermodal networks to achieve resource complementarity and optimization. Based on this, this paper comprehensively considers the utilization of sub-network capabilities, determines the specific channels and capacity constraints of the air-rail composite network, and constructs a physical network for air-rail intermodal transportation between major cities in China. For Air-rail Intermodal Service Network. Developing an optimization model for air-rail intermodal network based on the transportation capacity constraints of intermodal channels, aimed at minimizing transportation costs for both operating parties while maximizing the transportation of intermodal passengers, with a focus on co-creating value for enterprises. Specifically, the model targets the selection of specific routes and intermediate cities for OD pairs, considering the characteristics of the model. Additionally, comparing the results obtained from solving the model using genetic algorithms and CPLEX, and designing genetic algorithms for solution to determine the specific paths between OD pairs and the choice of intermediate cities. Finally, 53 major cities in China are selected for case study.

Driving Energy Savings in Railways Through Speed Profile Optimization and Regenerative Braking Synchronization

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Energy consumption in railway systems is substantial and it represents a significant portion of operational costs. Therefore, adopting energy-saving strategies is crucial to improve both sustainability and efficiency. This paper introduces a novel approach to saving energy in railways by the synergistic application of two key strategies: optimizing train speed profiles and maximizing regenerative braking energy through synchronized timetables of the urban fleet. The first strategy involves fine-tuning of the train's speed throughout its journey to establish an optimal balance between reduced traction energy consumption and adherence to the operational requirements. The second strategy enhances energy efficiency by synchronizing a leaving train acceleration and an incoming train deceleration to maximize the regenerative braking energy. We utilized the Genetic Algorithm (GA) to develop a proprietary algorithm to simulate energy consumption of the fleet and design the optimal timetable for energy saving. A successful trial implementation of the proposed approach was executed in collaboration with a metro operator, resulting up to 9% saving in traction energy. This results closely matches the simulation, highlighting the strong potential of our solution to significantly reduce energy consumption in railway operations.

Weak points of European railway digitization practices undermining interoperability and optimization

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The design, maintenance, and availability of digital data of railway operations is the basis and backbone of many operational tasks and all the related optimizations. The latter include route planning, assignments of rolling stock and other resources, etc. The European legislation provides a proper framework; both digitization and interoperability are considered with priority. Yet the everyday experience of RailNaviGo Ltd., as a provider of integrated software systems for railway freight transportation, shows that the implementations of the respective IT systems contain a number of shortcomings which may seem minor, yet they appear as relevant obstacles when maintaining these data or using them, especially when performing complex calculations or optimization on their basis. The inconsistencies in infrastructure, vehicle, and railway traffic data accumulate and pose a relevant obstacle of railway IT developments, especially when cross-border interoperability is relevant. This has negative effects on the competitiveness of railways with other freight transportation modes. In our poster we provide a systematic collection of such shortcomings observed in everyday practice, and formulate constructive recommendations for their resolution. This information can be helpful for those who deal with optimization problems on real-life European railway data, serving as guidance for data cleaning and preparation. Meanwhile we hope to attract the attention of various stakeholders of the railway community, thereby achieving impact on railway IT practice. This could contribute to the improvement of European railway IT systems, inline with the priorities of the respective legislation. The improved data structures could give more room to practical applications of railway optimization.

Some remarks on multistage sorting in hump yards

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The problem of multistage sorting in hump yards is to transform the inbound sequence of incoming freight cars into one or more ordered outbound sequences (outbound trains). The number of back-and-forth movements of the humping engine has to be minimized (the number of sorting stages has to be minimized). Known procedures (see Hansmann, see Jacob/Marton/Maue/Nunkesser) Provide one exit track per train to be formed. A classical hump yard consists of an inbound group followed by a hump followed by the classification group followed by the outbound group. Each track of the classification group is usually. It is therefore reasonable to use every track of the classification group as an exit track. An essential measure of sortedness is the number of chains. A chain of an outbound train is a maximal subset of cars with consecutive outbound positions and monotonicly increasing inbound positions. The chains of any train can be ordered in a natural way. One can proceed as follows.

- Fix. for each track, a set of consecutive chains of a certain train. The maximum number of chains per track should be minimized. (Let ni be the number of chains of the i-th train, N be the number of chains at all, and K be the number of available tracks. Then the number ki is an integer close to K ni/N)
- Apply simultaneous multistage multitrain sorting in parallel, for each track separately. All freight cars are now on track. The number of chains is reduced to one per track.
- Distribute each chain to its corresponding track..
- The outbound engine concatenates the chains belonging to the same train to one sorted train.

Safety orchestrator as a tool for increased railways network resilience

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The modern railway network is an intricate web of technology, communication, and infrastructure, demanding robust safety and security measures to ensure resilience against threats and disruptions. This poster introduces the concept of a Safety Orchestrator, a pioneering tool designed to enhance the resilience of railway networks through comprehensive safety and cybersecurity management. The Safety Orchestrator leverages advanced algorithms and artificial intelligence to monitor, predict, and mitigate risks in real-time. By integrating data from various sources, including sensors, control systems, and external threat intelligence, the orchestrator provides a holistic view of the network's safety status. Key functionalities of the Safety Orchestrator include automated incident response, predictive maintenance, and adaptive threat detection. The orchestrator's ability to seamlessly coordinate between cybersecurity and physical aspects ensures a unified approach to risk management. This results in reduced downtime, improved service reliability, and enhanced passenger safety. The paper will present case studies demonstrating the effectiveness of the Safety Orchestrator in real-world scenarios, highlighting its role in preventing accidents, managing emergencies, and ensuring continuous operations. Moreover, the discussion will extend to the orchestrator's scalability and adaptability to future technological advancements, underlining its potential as a long-term solution for resilient railway networks. Attendees will gain insights into the implementation process, challenges encountered, and best practices for integrating such a tool into existing railway infrastructure. The Safety Orchestrator represents a significant step forward in safeguarding the railways, ensuring they remain a secure and reliable mode of transportation in an increasingly complex world

Research on Key Technologies of Train Schedule Preparation System Based on Distributed Peer-to-peer Network

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Train schedule preparation is the core of the train transportation organization plan. With the rapid growth of China's railway network, train schedule preparation work is developing towards normalization. A new generation of train schedule preparation system is constructed using cloud platform technology system To improve the automation, intelligence, and informatization level of the system. The overall architecture, technical architecture, and network architecture of the system are designed to achieve interconnectivity and resource sharing with upstream and downstream systems through the distributed peer-to-peer network of the cloud platform; This system has surmounted multiple key technological difficulties, including researching real-time cloud synchronization of graphing data, real-time calculation of graphing indicators, real-time cloud backup and redundant storage of train schedule preparation data, large-scale group collaborative graphing, and integrated train schedule preparation terminals. The development of this system forms the core functional modules that cover the entire process of train schedule preparation work.The new generation of train schedule preparation system has been applied to on-site train schedule planning work, with significant improvements in functionality, performance, and safety. It is of great significance for innovating the management mode and work process of train schedule preparation, and improving the level of informationization and intelligence in train graphing.

A Spatial-Based Method of Railway Track Gauge Measurement Based on Lidar Data

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This paper presents a novel spatial-based method for railway track gauge measurement using LiDAR technology. Traditional contact-based methods face limitations in terms of efficiency and accuracy, particularly in complex environments, while non-contact methods often struggle with noise caused by intrusions such as vegetation. To address these challenges, we developed a spatial algorithm that processes LiDAR data to remove noise and accurately identify key points on the rail head for gauge calculation. Our method was tested on a Canadian rail section and compared with other two approaches. Results show that the proposed method provides more accurate gauge measurements in both straight and special track areas, with accuracy significantly improved due to the denoising process. The study demonstrates the effectiveness of using LiDAR data for precise railway track geometry monitoring and highlights the potential for broader applications in railway maintenance.

THU-2-A: BREAK + POSTER SESSION

Time: Thursday, 03/Apr/2025: 11:00am - 12:00pm · *Location:* POT/168/S

Improving the Performance of Rail Yards by Integrating Hump and Flat Shunting Schedules

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Technical yards are key components of rail networks, and their performance directly affects the network efficiency. To improve the performance of yards, this study proposes a new shunting method that integrates hump and flat shunting schedules to reduce the number of tracks used and shunting costs. This method preserves the advantages of the hump and flat shunting methods. Compared to hump shunting, which directs railcars (via gravity) to classification tracks for simple and sequential coupling, hump and flat shunting allows further sorting the railcars on tracks (after humping) through push-pull operations to reduce the number of tracks used and shunting costs. Compared to flat shunting, which sorts railcars through push-pull operations, hump and flat shunting optimizes the initial locations (hump shunting schedules) of railcars to reduce the total shunting cost. An integer linear programming model was designed to formulate the hump and flat shunting problem. A hybrid adaptive large neighborhood search and branch-and-bound algorithm was designed to efficiently solve the model. In numerical experiments, the hump and flat shunting method outperformed both the existing hump and flat shunting methods. Compared to the hump shunting method, the number of tracks used was reduced by an average of 6.1% and a maximum of 57.1%. The shunting cost was reduced by an average of 17.5% and a maximum of 47.6%. Compared to the flat shunting method, the shunting cost was reduced by an average of 33.4% and a maximum of 67.9%.

Section Maximum Carrying Capacity Calculation with CTC Data of High-speed Railway

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Targeting on recovering disturbed scenarios back to the operating timetable as soon as possible, one idea is to reduce both the headway and travel time in sections without changing the infrastructure or train diagram structure. In this paper, firstly, based on the compression principle of UIC406 for calculating section capacity, the concept of maximum carrying capacity was proposed on account of both the minimum headway and minimum travel time of each train type, which can be obtained from historical CTC data especially during rush hours. Secondly, the maximum carrying capacity calculation model was established and demonstrated by obtained CTC historical data of Xuzhou East-Nanjing South section downstream of Beijing-Shanghai high-speed railway. It was indicated from analyzing the CTC data that the headway and travel time in sections are more affected by the train stopping scheme than by the difference in train speed performance. Train type based on stop number (train stop type) was therefore put forward and corresponding maximum average speed calculation was given. The train headway type was proposed and divided into nine categories, and the minimum headway of each of the nine train headway types were determined for the studied sections. Finally, the maximum carrying capacity of each studied section was obtained based on compressing the operation diagram structure according to the calculated minimum headways and minimum average travel times. The results showed that the section maximum capacity was greatly improved compared with the capacity consumption, and it was increased 4% - 8.5% over actual capacity.

Methodologies to Identify Non-electrified Railway Lines to Be Convert to Hydrogen

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Although the rail transportation system is generally considered to have one of the lowest environmental impacts, this is not always true. Indeed, in the case of non-electrified railway lines, the propulsion system typically is based on diesel engines. The commonly adopted solution to improve the environmental sustainability of a diesel rail line is its electrification, which consists of constructing the overhead line, installing the related substations, and replacing and upgrading the rolling stock. However, in some cases, the electrification costs may not be justifiable due to the low number of passengers served by the considered line. In these cases, the conversion to hydrogen may be considered as an intermediate solution to the problem. In this context, the paper proposes a methodology to identify non-electrified rail lines that could potentially be converted to hydrogen propulsion.

A Framework for Integrating CBTC in Axle Counter Failure Management

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The Axle Counter system is widely used in global rail transport, including in Communication-Based Train Control (CBTC) systems. However, axle counter failures continue to impact CBTC operations. Some axle counter systems include features for the automatic reset of failed axle counter sections by considering associated virtual sections logically overlay on the sections of interest. Nevertheless, current implementations of automatic resets in axle counter systems are limited primarily to specific faults, such as miscounts, and do not address hardware failures, thus the failure persists in the system. In cases of failure, the CBTC system can manage the situation by accurately locating CBTC-equipped trains, enabling it to ascertain whether an axle counter occupancy signal is erroneous or a genuine train occupancy. However, if non-CBTC-equipped trains operate in the same area, the CBTC may struggle to accurately identify fault occupancy once a non-CBTC-equipped train has passed through the affected section due to safety considerations. To enhance functionality, the CBTC system could leverage reports of virtual sections status from the axle counter system along with position data from CBTC-equipped trains. This integration would facilitate the identification of non-CBTC-equipped trains and enable the effective determination of fault occupancy, thereby improving overall system reliability and operational safety. This research proposes a practical framework for integrating axle counter failure management within existing Alstom's CBTC systems, leveraging interface data available in current technologies. Additionally, it addresses the challenges of implementing this functionality and provides recommendations to overcome these obstacles.

A risk-based evaluation approach for scheduling train dwell time

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This paper introduces the risk of dwell time delay evaluation approach to address the challenge of evaluating dwell times at high-passenger-volume stations in high-frequency metro systems. Dwell times play a critical role in high-frequency metro systems in determining line capacity, passenger journey times, and resource needs. Delayed or inconsistent dwell times can lead to longer train journeys, passenger delays, and train knock-on delays, affecting service reliability and passenger satisfaction. The risk-based evaluation approach offers a comprehensive and valuable trade-off analysis for service planning by considering the probability of dwell time delays and their consequences on passenger journeys. It enables transportation authorities and operators to make accurate decisions for optimizing train operations and passenger flow. This approach proposes an improvement over existing dwell time evaluation approaches that primarily focus on predicting dwell time representative values, which can be inaccurate in crowded systems and do not take the impacts of dwell time delays into account. The development of a bivariate dwell time delay function enables the estimation of the probability of trains with a certain level of passenger volume being delayed by a certain amount of time. By evaluating dwell time consequences using passenger-weighted journey time, the approach effectively calculates the risk of dwell time delays. This risk evaluation approach fulfils the research aim of evaluating uncertain dwell time delays and improving high-frequency metro services. This paper demonstrates the application of this risk evaluation approach on the London Underground's Victoria line case study. We use the approach to determine optimal planning decisions. The best-case planning strategy with the lowest risk of dwell time delays was identified when planning a 20-second dwell time margin in the timetable and maintaining a crowding level on trains at 70% of the train's full capacity.

Comparison of Rail Transport Organizations: A Case Study of Thailand and Sweden

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Railway systems play a key role in promoting sustainable mobility for both intercity travel and urban mobility. Railways are guided systems with high safety standards, requiring a variety of subsystems to operate effectively. However, the development and operation of railway systems require significant financial investment. In many countries, strategies have been adopted to restructure railway organizations which impacted the government's financial standing and competition within the railway industry. Moreover, the organizational structure directly affects the responsibilities within passenger rail transport, which in turn impacts the overall travel experience. The passenger journey involves several stages, from planning the trip, purchasing tickets, boarding the train, to interconnecting with other transport systems. All these stages must be seamlessly coordinated between organizations to attract more people to choose rail transport. The railway organizational structure, therefore, significantly influences rail service outcome. This research aims to address how the railway organization impacts rail passenger services in sub-urban, regional, and intercity train services. A comparative case study has been examined and were analyzed two different railway organization structures from Thailand and Sweden. Trafikverket, from Sweden, oversees the national rail infrastructure and private operators managing train services under a competitive framework. Swedish regional agencies make decisions about the public transportation for their cities including urban rail. There are four cities in Sweden with urban rail system (Stockholm, Göteborg, Norrköping, and Lund). In Thailand, intercity rail is planned by the State Railway of Thailand (SRT). Mass Rapid Transit Authority (MRTA), Bangkok Metropolitan Administration (BMA), and SRT are metro project's owner in Bangkok. Bangkok is currently the only city with urban rail system in Thailand.

Design of Model Railroad for Railway Operations Learning

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Railway operations at currently tend to be centralized and integrated by complex subsystems. A computer-based control center manages and monitors signaling objects in a railway network, including turnout, traffic signal, and level-crossing gate. For railway engineering education, site visits to experience actual operations is good practice for learning and understanding. The downside is that students cannot also take part in real operations due to potential limitations and disruptions. This research, therefore, focuses on design to use a model railroad to imitate actual operations. We would like to perform core railway principles and operations using the model railroad with control by dispatching simulation software as an example of interactive learning. The research investigates the core principles of railway operations, the basic components of model railroad, and the important operating data of dispatching simulation software. We design a data architecture for communication between the model railroad and the dispatching simulation software. A prototype case is developed based on this design to examine the representation of railway principles. The results show that the prototype properly demonstrates the core principles of fixed block signaling, including route reservation, traffic signal display, and train detection by track circuit. Core commands from the dispatching simulation software consist of throwing turnout position, setting signal to proceed, and setting signal to stop. Core responses from the model railroad are occupied track, and cleared track. Wayside signals and turnouts change their states accordingly. In this research, train control is manually operated. To enhance the Grades of Automation, we recommend exploring on using automatic train control together with automatic route setting. Additionally, an integration with electrical control system, such as SCADA, is suggested to further expend the research area with model railroad.

Collaborative Optimization of Flexible Composition Passenger Train and Freight Train Operation Plan

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Developing under-exploited passenger rail networks is emerging as an alternative for freight transport. In light of this, this paper investigates the collaborative optimization of passenger and freight train operation plans within the rail networks. A sharing-train mode is adopted for passenger trains, which enables the flexible composition of both passenger and freight carriages, thereby optimizing the configuration of passenger trains to cope with the different situations of passenger flow demand in the network. Under conditions of saturated passenger flow, the entire train is dedicated to passenger transport. When the passenger flow is insufficient, freight can be transported either by dedicated freight trains or by converting some passenger carriages into freight carriages, utilizing the redundant capacity of passenger trains to improve train utilization. Through the sharing-train mode, it is possible to simultaneously meet the demands for passenger and freight transport across different segments, thereby improving train efficiency. Station platforms can load and unload both freight and passengers. Unlike traditional phased optimization methods for passenger and freight train operation schemes, this paper proposes a new integrated optimization approach for train operation regions, stop plans, and the distribution of passenger and freight flows. The model incorporates constraints related to flexible train composition, train capacity, passenger load factor, freight load factor, and segment selection. A collaborative optimization model for passenger and freight train operation plans is formulated as a mixed-integer linear programming problem, with the objective of minimizing total operational costs. Numerical experiments are conducted to compare and analyze the differences between the phased optimization model and the collaborative optimization model using conventional railway corridors as a background. The study investigates the effects of varying train utilization requirements, operational segments, train composition, and stop frequencies on the experimental results to demonstrate the applicability and superiority of the collaborative optimization approach.

Conflict-centric Dynamic Decompositions for the Real-Time Railway Traffic Management Problem

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Railway networks often suffer unforeseen delays due to external factors, which can cause accumulations of cascading delays as trains require the same piece of track, leading to first-degree conflicts. In order to minimize total system delay, strategies must be undertaken to predict and resolve conflicts. Various optimization approaches exist to do so. However, these approaches may struggle to cope with large, complex, or busy networks. This paper proposes a heuristic algorithm for conflict resolution, which uses conflict predictions to draw decomposition boundaries around trains likely to be impacted by specific decisions. Possible solutions to predicted conflicts are hypothesized without considering other trains in the area, and then compared with those trains to collect further predictions of higher-degree conflicts, recursing until reaching the preset depth limit of n. Different branches of conflicts are then assembled into sub-instances, which are intended to be easier and quicker to optimize. The algorithm performance can depend closely on n: lower values of n may lead to quickly found but myopic solutions, while higher values may lead to very slow but overall better solutions. To understand the impact of n, we conduct a sensitivity analysis. Trials are run over a period of a few hours of traffic in the control area including the French station of Saint Lazare, in Paris. This is a terminal station where trains either complete or start their service, and are involved in turnaround operations. A very large number of trains pass through every hour, often more than 100, and very complex traffic situations emerge. When factoring in the real-time constraints of the problem, which can limit the exploration of the search space, our decomposition approach with a proper setting for n leads to improved results over a classic state-of-the-art approach from the literature.

Detection support system for point machines systems

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The railway infrastructure relies on turnout systems, essential for guiding trains. These systems, comprising components like point machines, switches, and frogs, ensure smooth operations. However, their complexity makes them prone to malfunctions, potentially leading to delays or catastrophic accidents. Consequently, monitoring these systems is vital for maintaining operational integrity and passenger safety. One major challenge lies in the scarcity or even lack of labeled data. Sensor-equipped railway turnout systems generate vast amounts of electrical data, which can be leveraged for fault detection and improve system reliability. In addition, data samples are often unlabeled, making it difficult to apply fault detection approaches effectively. The data vary due to weather, load, and maintenance interventions. This compounded complexity highlights the importance of unsupervised learning techniques, which can handle unlabeled data to detect hidden patterns and support fault detection without predefined labels. In addition to the scarcity of labeled data, the challenge of imbalanced data is also prominent in railway turnout systems. The system operates under multiple normal operating conditions, resulting in a highly imbalanced dataset. Normal operating conditions are represented in a non-uniform way, discriminating against abnormal operating modes that are insensitive. This work focuses on detecting abnormal signal traces from sensors in a railway turnout system. The goal is to monitor the system's health as part of a fault detection task. The proposed unsupervised framework includes segmentation, feature extraction, and anomaly detection, providing a comprehensive solution for enhancing railway system reliability. Segment-based and curve-based indicators have been proposed for detection purposes. Numerical experiments have been conducted on an industrial dataset. The dataset comprises power consumption signals from more than 50 railway turnouts, each with a unique configuration that influences the shape of its curves. This dataset presents several challenges, including its large size, lack of labels, and class imbalance.

Simulation Model of Braking Curves for ETCS-equipped Trains on a Mixed Traffic High-speed Line

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The European Train Control System (ETCS) is essential for unifying Europe's railway networks, ensuring seamless cross-border operations, and enhancing safety. In Serbia, ETCS has been implemented on the mixed traffic high-speed line to improve efficiency and align with EU standards. To analyze the system's impact on Serbian railways, a simulation model was developed in the Python programming language. This program models the braking curves for Gamma and Lambda trains, following the safety measures prescribed in Subset 026 by the European Union Agency for Railways (ERA). By simulating real-world braking scenarios, the program provides valuable insights into the performance of ETCS on Serbian trains. The results are compared with the ERA's "Braking simulation tool" for validation, ensuring the program accurately reflects the braking behavior under ETCS control. The flexibility of the Python program allows for quick adjustments and testing of different train types and conditions, making it an adaptable tool for further analysis of ETCS implementation across various routes. This approach supports ongoing improvements in safety and efficiency, facilitating the testing of mixed traffic trains with diverse onboard equipment and systems.

The Rail Bonus in Local Public Transport – An Empirical Analysis of the Preference for Rail-Guided Modes of Transport

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When choosing a means of transport, trains and trams are favored over buses. This inherent preference for rail-guided modes of transport is known as the rail bonus. The calculation of a rail bonus makes the forecast of user numbers more precise and leads to realistic demand models, which are essential for the dimensioning and economic evaluation of transport systems as part of a cost-benefit analysis. Before an infrastructure project is realized, a cost-benefit analysis is carried out. The most important factor on the benefit side is the predicted number of users before and after a change of service. If no or too low a rail bonus is assumed, this can lead to the user numbers being underestimated and the economic benefit being calculated too low. The aim of this study is to calculate a flat-rate value for the rail bonus in local public transport in Germany and to compare this with the value in the Standardized Assessment for Transport Infrastructure Investments. To determine this value, a utility function was created for the demand of the transport modes car, bus and tram (urban) respectively regional train (rural) and then a discrete choice experiment (stated preferences) was carried out. The data was obtained with the help of a survey that was distributed throughout Germany. From 891 people who completed the survey in full, 21,384 choices were generated. The result shows that the probability of use of track-guided vehicles is 77.5 % higher than that of buses for the same objective parameters such as journey time and costs. This value is underestimated in the Standardized Assessment. A further finding is that a transfer between buses is rated more negatively than between trains, and the journey time on buses is also perceived more negatively.

Review on the Modelling of Modular Pod-based Rail and Road Transportation

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The PODS4Rail-project, part of EURail Flagship Area 7, focuses on the development of a futuristic mobility system where autonomous and modular vehicles ("PODS") are interchangeable on rail and road infrastructure. Moreover, the system includes both passenger and goods transportation. Recent research and developments have provided a number of concepts that provide the key building blocks for future automated, modular, and multi-modal mobility systems. These systems integrate and coordinate rail-based and road-based transportation, with the ability to merge goods and passenger transport, and combine the strengths of both planned and flexible (on-demand) systems. The poster presents the current state of the art of the approaches used for analysing, modelling and simulating such concepts found in literature. Focusing on modular, on-demand rail and road passenger transport, logistics and intermodal transportation, it synthesises the current knowledge regarding such systems and identifies research gaps where the system developed within PODS4Rail can play a key role.

Modelling Public Transport Travel Time Uncertainty using Risk Measures

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In public transport (PT), travel times are inevitably uncertain, leading to issues such as delays, missed transfers, and schedule sliding, potentially hampering a sustainable modal shift. Thus, deterministic timetables alone are insufficient for decision-making among PT participants, making it necessary to address the randomness in travel times. A way to quantify the uncertainty accompanying decisions is to assign a real number to the travel time probability distribution, such as travel time reliability metrics. However, these often measure non-constancy or the probability of a certain delay, neglecting both the variability and potential extremes in travel times. For instance, a trip that is generally reliable may still experience significant delays occasionally, which can be perceived as risky. This research utilizes risk measures to deal with PT decision-making under uncertainty. Risk measures, well-known in finance, are surrogate values not only accounting for the possibility of perturbations but also for the degree and consequences. We propose a theoretical framework, establishing axioms similar to those in finance to characterize delay risks. Here, we consider two different perspectives: the passenger, focusing on time of departure and route choice, and the operator, concerned with the design and accompanying systemic risk of an entire timetable. Our axioms include (finance) risk properties like monotonicity and subadditivity, along with PT-specific ones like transfer penalty, addressing different practical and theoretical characteristics of risk. This provides a rigorous mathematical foundation for analyzing delay distributions and evaluating the quality of used reliability and risk measures, including Value at Risk and Conditional Value at Risk. To validate the established framework, we use simulation data replicating real-world travel time distributions in public transport. Considering various attitudes towards risk, we systematically assess how well the framework captures the complexities of decision-making under uncertainty.

High-Speed Train Timetabling Method Considering Route Conflict at Stations with Limited Capacity

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For China's high-speed railway network, the generation of train timetables and the subsequent allocation of station tracks proceed in well-defined stages. Typically, the process begins with timetable draft including train preliminary departure and arrival time at stations, subsequently serves as the foundation for allocating station tracks to trains, and the timetable draft shall be adjusted if feasible station tracks cannot be found. Nevertheless, the complexity arises when considering stations with limited capacity, which usually causes too many timetable adjustments or low capacity utilization of limited stations. Inbound and outbound trains from various directions needs to use suitable tracks to pass or stop at stations, or turn around when they come from and go back to EMU depots. Hence, we introduce an innovative train timetabling approach that focuses on station route conflicts, to confirm that if it possible to allocate tracks before timetabling, which is better for capacity utilization and timetabling efficiency. First, we formulate an arrival-departure track allocation model with the goal of maximizing station capacity utilization and input of different train operation demand, to determine the departure and arrival sequences for each train at the limited station. According to the established order, a timetabling model is built based on the train route conflict at the limited station, which resolve conflicts between trains at section-level and station-level. To effectively resolve this model, we design an efficient alternating direction method of multipliers (ADMM) decomposition algorithm. Finally, a real-world case based on the Beijing-Zhangjiakou high-speed railway, which is an important support for the 24th Winter Olympic Games, is studied to prove the effectiveness and efficiency of the proposed model and algorithm.

Evaluating the effectiveness of railway climate change adaptation - a practical study between the United Kingdom and Taiwan

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It is evident that the effects of climate change are growing rapidly and heavily impacting critical infrastructures, including railway systems. Now that more extreme weather events are impacting railway systems, adaptation is necessary to maintain an acceptable level of climatic risk. In the literature, railway climate change adaptation is understood as a series of strategic actions planned to enhance the resilience and robustness of a railway system to resist, absorb, and recover from increasing climatic risks which lead to the disruption of railway systems. Adaptation strategies should consider both existing and future risks of extreme weather and adverse climate and provide clear pathways in terms of implementation timeframe for all adaptation actions. Therefore, adaptation should now be part of "business as usual" instead of standalone dedicated projects, and therefore adaptation planning should be integrated into railway safety management systems, asset management, resilience planning, and other strategic planning and daily operation decision processes. It logically follows that adaptation must be approached with similar robustness of international benchmarks such as safety and operational performance so that operators and managers can gauge the appropriateness of their initiatives. To evaluate the effectiveness of railway climate change adaptation, a systematic and comprehensive evaluation method is important. In this paper we propose a framework comprising multiple attributes to evaluate how effective or comprehensively a railway company performs and integrate adaptation in their planning, construction, operation, and maintenance. Each attribute is further divided into sub-attributes to evaluate whether railway companies have undertaken certain adaptation actions and to what level. A case study is conducted to evaluate and benchmark the implementation of climate change adaptation between the United Kingdom and Taiwan to demonstrate the framework. The proposed framework is valuable for railway operators and regulators for railway climate change adaptation planning and performance evaluation.

Foreign object detection and evaluation at railway crossings

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Foreign objects invading the railway tracks at railway crossings may cause serious safety accidents during train operation. In order to reduce the probability of railway crossing accidents, there is great potential for efficient detection and early warning of targets around the train tracks. This paper takes the railway crossing as the background and uses the camera to collect the object images appearing beside and on the track. The objects appearing around the track are classified into 10 categories according to vehicles and pedestrians through a self-made data set. Based on the self-made image data set, the currently popular object detection model YOLOv11 is used for training and prediction. In addition, not all targets near the track will pose a threat to the driving safety of the train. Therefore, this paper proposes a state evaluation strategy that comprehensively assesses the object's condition based on its current state, moving speed, and distance from the track, so as to achieve the purpose of reducing safety hazards during train driving. In the prediction experiment of the YOLOv11n model, the results show that the mAP50-95 of the railway crossing data set proposed in this paper can reach 78%, and the mAP50 can reach more than 90%.

Heuristic Approaches for fleet maintenance allocation

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This research addresses the critical challenge of optimizing rolling stock maintenance scheduling to enhance train availability and meet increasing transport demand. Traditional periodic maintenance often results in unnecessary downtime, impacting service reliability. Our study introduces flexible maintenance cycles, allowing operators to adjust schedules based on actual train usage, thereby reducing downtime and improving fleet availability. A key focus is on balancing maintenance costs with the risk of system failures. By integrating deterministic maintenance costs and the associated risk of failures, our approach offers a cost-effective alternative to static schedules. The research also tackles the complexity of coordinating multiple maintenance activities for different subsystems within a train, each deteriorating at varying rates. Our scheduling method ensures efficient coordination, minimizing overall downtime and avoiding unnecessary operational delays. The methodology combines a detailed modeling framework with a heuristic approach based on Design Theory to address the NP-hard problem of scheduling rolling stock maintenance. The problem is modeled as a multiflow network, accounting for limited resource availability across different depots and constraints on fleet availability. A tailored heuristic algorithm incrementally schedules maintenance activities, incorporating local search techniques to enhance performance and computational efficiency. Preliminary results indicate that the heuristic effectively balances maintenance scheduling costs with operational constraints, maintaining high train availability while adhering to resource limitations. The heuristic demonstrates robustness across various scenarios, adapting to changes in resource availability and operational demands. The main innovation lies in the novel problem framework that adjusts maintenance intervals based on operational time rather than fixed cycles. This approach, coupled with a heuristic algorithm capable of solving large, complex instances, provides a flexible and practical solution for real-world maintenance scheduling challenges.

Investigation of slack time deployment in train scheduling considering reliability and capacity

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Slack time is imperative in railway operational planning because proper slack time in train timetable scheduling offers flexibilities that reduce train delay occurrences and propagations. Meanwhile, adding slack time also affects rail capacity, and unnecessary slack time reduce system capacity and operational efficiency. Therefore, the allocation of slack time intrinsically represents a trade-off between rail capacity (efficiency) and system reliability (quality). This study proposes a new method to derives slack time that minimize its negative impact on rail capacity while effectively managing practically operational stability. Slack time can be categorized into running supplement time and headway buffer time. In practice, the slack time for many railway operators is derived through rules of thumb and experience-based calibration. This study proposes a data-driven, mathematical-based procedure for determining proper slack time. For running supplement time, the approach considers operational variability and heterogeneity by comparing scheduled interstation running time with the actual running time obtained from real-time Automatic Train Protection (ATP) records to construct a probability distribution. Headway buffer time is derived by evaluating the impact of different train types on rail capacity. Specifically, the method standardizes headway across all preceding train combinations, uses homogeneous trains as the baseline, and assigns weights to other train types contingent on their impact on capacity, resulting in a more precise buffer time calculation. A case study using Taiwan Railway Corporation (TRC) data is presented to demonstrate the proposed methodology. The proposed method will be valuable for railway operators as it can generate slack time value for train scheduling planners that ensures system reliability while elevating rail capacity. Additionally, the formula includes dynamic adjustment capabilities, enabling slack time to adapt to operational changes such as vehicle replacements or track geometry improvements. This allows synchronization with real-world needs, achieving an optimal balance between system efficiency and quality.

Modular multimodal freight transport systems

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This paper investigates the potential improvements in multimodal freight systems through the use of modular vehicles (MVs), aiming to enhance operational adaptability and integrate these vehicles within the mobility-as-a-service (MaaS) concept. The research examines a specialized form of the Pickup and Delivery Problem (PDP) adapted for rail and road logistics, presenting a new mathematical model for the Pickup and Delivery Modular Vehicle Routing Problem (PDMVRP) that includes road and rail. This model tackles significant operational issues such as routing of MVs on road, platooning and the scheduling of MVs on railways and transfers between road and rail MVs. A practical example in a regional road and railway network demonstrates the effectiveness of the proposed model, indicating their ability to decrease costs(energy and emissions), shorten travel times, and boost the efficiency of rail capacity, thereby promoting the advancement of MV usage in future transport systems.

Optimizing Regional Rail: Sustainable Alternatives for Serbia's Non-Electrified Lines

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A dramatic increase in mobility in urban and suburban areas, where more than half of the world's population resides, highlights the critical importance of regional and suburban rail passenger traffic in meeting transport demand. The development of regional rail is increasingly prioritized in transport policies and by decision-makers globally, as it offers an environmentally sustainable alternative to the private vehicle use by reducing pollution and congestion, while combining the flexibility of urban transport with the capacity and efficiency of conventional railways. Non-electrified regional rail lines, typically served by diesel multiple units (DMUs), pose significant challenges in terms of environmental pollution and resource scarcity. This paper employs the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in order to determine and verify the optimal alternative for regional passenger traffic on the Beograd Centar - Pančevo - Vršac line in northern Serbia, one of the most vital regional lines in the country. The assessment considers the following criteria: a) the costs of purchasing, operating, maintaining and repairing the rolling stock and providing energy, b) the costs of installing and maintaining the operational infrastructure, c) operational friendliness and d) environmental compatibility. The analysis evaluates three suitable alternatives to DMUs: electric multiple units (EMUs), battery-powered multiple units (BEMUs) and hydrogen-powered electric multiple units (HEMUs). The results suggest that innovative propulsion system concepts, such as BEMUs, along with the proven EMUs, offer significant improvements in energy efficiency and reductions in overall environmental impact over a 30-year period, representing the most advantageous investments in this context. In addition, sensitivity analysis is performed to investigate the robustness of the model and determine the impact of the proposed criteria on the overall results and their applicability in the decision-making process.

Railway Timetable Rescheduling through Learning-based Methods

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Railway systems suffer from disturbances in operations, such as extended section running times caused by temporary speed restrictions and prolonged dwell times at stations due to unexpected passenger volumes. These disturbances cause deviations from the original timetable and negatively impact service reliability and passenger experience. Effective and timely rescheduling measures are crucial in reducing the impact of these disturbances. Existing timetable rescheduling models that rely on optimization-based methods often struggle with computational inefficiency, especially when dealing with scenarios involving a large number of train services. To address these challenges, we propose a learning-based timetable rescheduling framework that considers scalability in its formulation to reduce the growing computational burden associated with an increasing number of train services. The proposed framework decomposes the complex rescheduling problem into multiple subtasks, facilitating a systematic approach to managing extensive railway networks with numerous stations and train services. A high-level agent, functioning as a centralized traffic controller, is responsible for decomposing the overall deviation reduction task into subtasks at a low level and assigning them to individual train services with the primary objective of minimizing the time required to restore the original timetable. Low-level agents, acting as distributed train dispatchers, are tasked with rescheduling the timetables of their assigned trains. These low-level agents employ various dispatching strategies, facilitated by inter-train communication, to search for optimal rescheduling solutions while adhering to operational constraints such as minimum headway requirements. The low-level agents utilize an actor-critic architecture to generate continuous control decisions for dwell and running times, enabling them to learn and optimize their performance. Knowledge-sharing mechanisms amongst the low-level agents enable faster and more robust learning. Furthermore, advanced exploration methods are integrated to enhance the efficiency of the agents' training process.

THU-2-B: BREAK + POSTER SESSION

Time: Thursday, 03/Apr/2025: 11:00am - 12:00pm · *Location:* POT/161/S

Integrated optimization of train timetabling, rolling stock maintenance and assignment with short-turning strategy

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Efficient use of rolling stock is an important goal pursued by a railway agency or company. Although most of the existing studies have obtained operation plan with the lowest operating cost by minimizing the number of rolling stocks used, these studies ignore the practical requirements or do not consider the rolling stock assignment, which makes the plan difficult to execute or infeasible in actual operation. To solve this problem, this paper considers the rules of rolling stock circulation and practical constraints, and puts forward an integrated method of train timetabling, stop planning, rolling stock maintenance and assignment. In particular, the method simultaneously considers constraints such as limited train capacity, turnaround operation, time- and mileage-based maintenance rules, the finite number of available trains, and depot capacity. By introducing decisions involving rolling stock selection variables, formation types, considering the short- turning strategy of trains, a nonlinear integer programming model is developed to minimize the weighted sum of passenger travel cost and train operating cost, accounting for passenger and operator perspectives. The correctness and effectiveness of the proposed model are verified by numerical experiments, and a solver is employed to solve the model. The results demonstrate that, compared to the full-length strategy without considering rolling stock maintenance and assignment, the proposed method can effectively reduce the travel cost of passengers by approximately 38%, ensure the feasibility of the operation plan and the safety of the rolling stock. Moreover, the approach can also support decision-makers with different passenger and operator preferences.

A Study to Improve Average Speed of Korean High-Speed Railway

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This study aims to enhance the average speed of the Korea High-Speed Rail (KHSR). Since its inauguration in 2004, KHSR has faced several constraints that have limited its average speed over the past 20 years. This study analyzes four key factors contributing to these limitations. The first factor is the ballasted track-bed. Ballasted track-beds require periodic maintenance, during which speed restrictions are imposed. This study examines the potential improvement in average speed by replacing the ballasted track-bed with a slab track. The second factor is the low-height platforms (LHP). Several studies have confirmed that LHPs cause more delays during boarding and alighting compared to high-height platforms. These delays have become increasingly problematic for KHSR due to the growing number of passengers and their luggage. The third factor involves the speed code-based train control system. This outdated system restricts the operational speed according to the speed code, even though the infrastructure is capable of supporting higher speeds. We have identified over 10 sections within KHSR where speed is unnecessarily restricted in this way. The final factor relates to operational patterns. KHSR has not adopted the meet/overtaking operational pattern, despite its station spacing being much shorter than that of European HSR systems. This study proposes an optimal meet/overtaking schedule and analyzes the potential improvements in average speed from these new operational patterns. This study provides a quantitative analysis of the effects of these four factors and introduces basic directions of KHSR to improve the factors.

Advanced optimization for reliable and efficient public transport

Krzysztof Domino[1], **Wojciech Gamon[2,3]**

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The presented research aims to improve the resilience of public transport to disruptions by utilizing disruption mitigation with an optimization approach. The supreme goal is to enable the planning of reliable and optimal public transport, and in particular achieving and maintaining a high level of passenger satisfaction despite the occurrence and propagation of disturbances to increase the number of passengers using public transport. Public transport operations should primarily address the needs of passengers, both those who already use this transport and potential ones. Therefore, passenger satisfaction should be a key factor in selecting particular optimization problems and their objective. We focus in particular on the local rail transport system, where we select the meaningful optimization problem by consultation with the local railway operator and with the local society by online consultations. The public transport network in densely populated areas is often a complex structure that should be analyzed globally. Disruption that occurs in one location spreads along the network. This causes problems and subsequent dissatisfaction among passengers in other, often remote locations. To mitigate such problems globally a significant computational challenge appears. In particular, as the size of the analyzed network increases, the complexity of the computational problem rises sharply. Such optimization problems are usually formulated as integer linear programming (ILP). For large systems, it may be difficult to solve such problems in the adequate time it to respond to the disturbance in the real resilient public transport scenario. The choice of the particular algorithm to tackle such a problem is not straightforward and depends on its specifics. In this presentation, we will present algorithms (exact and heuristics) that are available to tackle such resilient transport optimization problems, accounting for the limitation in terms of the size of problems that can be tackled in a reasonable time with fine accuracy.

Analysis of energy-efficient train driving applications in real-world operations based on empirical data

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Recent research in Energy-Efficient Train Control (EETC) and Energy-Efficient Train Timetabling (EETT) has uncovered various strategies that can be utilized to reduce railway energy consumption without placing additional demands on the capacity or compromising the robustness of operations. Several railway undertakings have already integrated aspects of these methodologies both in daily operations by the implementation of Driver Advisory Systems (DAS) and in the timetable design process. The major passenger railway operator in the Netherlands, Nederlandse Spoorwegen (NS), utilizes a tablet-based DAS that provides coasting advice to train drivers, while also displaying the route, timetable, temporary speed restrictions and blocks occupied by preceding traffic. Despite the implementation of this system, historical trajectory data from real world operations in the Netherlands indicate variances in the extent of energy-efficient train driving application. These variations could lessen the energy-savings of EETC and increase operational costs. Hence, the main aim of this poster is to evaluate the application of the EETC strategy in real world operations under varying environmental and operational conditions based on historical timetable and train trajectory data, while identifying the causes leading to the observed differences. Subsequently, a literature review of train trajectory optimization techniques is conducted to examine the extent to which these causes are addressed. Finally, the real world applicability of these methods is discussed and future research directions are provided.

Automatic generation of train path envelopes for Automatic Train Operation

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Efficient railway operations are essential to accommodate growing traffic demand and to sustain high levels of system performance on heavily utilized corridors. Conventional train scheduling methodologies often face challenges in preventing train path conflicts arising from deviations in planned trajectories or operational uncertainties. To address this, we developed a framework to automatically generate conflict-free Train Path Envelopes (TPEs) for successive scheduled trains from a real-time traffic plan in a designated railway corridor. Specifically, the TPE is defined as a sequence of time targets or windows at key network locations (known as timing points) and serves as train trajectory constraints in generating conflict-free train trajectories aligned with the real-time traffic plan. The computational framework processes infrastructure and timetable data autonomously, identifies potential track occupation conflicts using blocking time theory across three typical train driving strategies and resolves them through the automated determination of intermediate timing points and dynamic adjustment of departure tolerances. Buffer times are incorporated into the blocking time bounds to tolerate train trajectory tracking errors.Lastly, the framework computes the earliest and latest feasible trajectories for each train. From this the TPEs are derived as a list of timing points with their time windows or targets. This framework not only optimizes track utilization by ensuring conflict-free train operations but also promotes energy efficiency by defining flexible and robust time-distance boundaries for train movements. The efficacy of the proposed framework has been validated through integration with FRISO (Flexible Rail Infrastructure Simulation of Operations), a microscopic simulation tool with discrete, dynamic, stochastic and deterministic properties. This development marks a first step towards a better link between railway traffic management and automatic train operation and is a cornerstone in Europe's Rail FP1-MOTIONAL project.

Economic Implications of Delay Generation and Propagation depending on Track Access Charges Mechanisms

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This research explores the relationship between railway delays, their propagation through the network, and the economic effects generated by these delays because of the various mechanisms of the Track Access Charges (TAC) and the performance regimes. Advanced methods are applied to assign the responsibilities of the primary delays and classifying their causes, they often overlook the connection between these aspects and their economic implications. The purpose of this study is to contribute to filling this gap by proposing a structured framework that combines the regulatory environment consequent to European Union's rail market liberalization. The standardized regulations for access to infrastructure, the capacity allocation and the slots pricing link Infrastructure Managers and Railway Undertakings performances by TAC mechanisms, which frequently include performance regimes based on bonuses and penalties to stimulate the increase of punctuality and enhance service quality. The methodology starts with a comprehensive analysis of TAC structures across European countries to identify the applied performance regimes, followed by a formalization of primary delays propagation under defined infrastructural and operational contexts. This process aims at measuring the effects of the sequence including a) generation of primary delays, b) assignment of their responsibilities, c) propagation of the delays and computations of bonuses or penalties under various performance regimes. The comparative analysis is based on relevant tests on cases studies in various railway networks. This research offers valuable insights into the dynamics between operational and economic strategies implemented to manage the liberalization of rail traffic. The findings of this study would contribute to a better understanding of how TAC mechanisms and performance regimes influence the efficiency and the financial sustainability of the railway sector.

Validation & verification for engineering datasets of trackside Control-Command and Signalling subsystems – a literature survey across disciplines

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The railway system is essential for mitigating the climate impact of passenger and goods transportation. Control-Command and Signalling (CCS) systems are vital for ensuring safe, reliable, and efficient rail operations. With plans to upgrade numerous outdated interlockings and train control systems at an unprecedented pace, there is an urgent need for efficient processes in planning, implementation, and particularly verification at each stage. This challenge spans multiple countries and involves various Infrastructure Managers (IMs), necessitating a focus on interoperability for the validation approach, considering diverse data formats, structures, levels of detail and national specifics. This study examines the current state of validation and verification procedures for engineering datasets of trackside CCS subsystems at DB InfraGo, the primary IM in Germany, which faces significant political and societal pressure. It also analyses innovative methodologies from other fields, such as EULYNX DataPrep and IFC-Rail for Building Information Modeling (BIM), as well as methodologies from different domains, including the Aeronautical Information Exchange Model (AIXM), pipelineML for underground facilities, and IFC-Road for BIM. The analysis considers several code-checking methods to identify future-proof tool support, particularly in light of diminishing human resources for programming and inspection within this sector. By leveraging model-driven approaches for knowledge representation and rule management, the study revisits various generic methods, including formal methods, business process modeling (BPM), and constrained natural language (CNL). These methods are assessed against criteria tailored for specific applications in trackside CCS engineering, such as managing high complexity in rules, adaptability to various data formats and structures, performance with large datasets, and the ability to enhance existing rulesets with minimal programming skills. The findings aim to improve the efficiency and reliability of railway infrastructure operations in the CCS domain while outlining research directions that emphasize the need for robust validation and verification processes to ensure resilient railway operations.

Optimizing Railway Timetable Feasibility using Reinforcement Learning

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Railway scheduling is a complex task that involves solving recurring instances of constrained optimization problems. Traditionally, each instance is treated as an isolated problem, leading to inefficiencies in computational effort and scalability. This research explores the application of reinforcement learning (RL) to optimize railway timetables by integrating the feasibility and optimization phases of the scheduling problem. The railway scheduling problem is typically defined by a set of linear and integer constraints that govern operational aspects such as minimum and maximum times for driving, dwelling, and headway, alongside routing and precedence decisions for trains. The timetable satisfiability problem focuses on determining whether a feasible solution exists while the timetable optimization problem seeks to find an optimal timetable based on criteria such as minimizing delays. This work introduces an RL-based approach that iteratively interacts with a satisfiability solver. The RL agent preselects some of the decision variables such as route or precedence choices, influencing the search space of the solver. Upon determining whether the selected variables lead to a feasible solution, the RL agent receives feedback in the form of rewards (for feasible solutions) or penalties (infeasibility indicated by the UNSAT core). The agent iteratively refines its selection strategy to improve the objective value, such as minimizing delays while maintaining timetable feasibility. By integrating the feasibility and optimization phases within a reinforcement learning framework, this approach explores the potential to develop more scalable algorithms for solving similar problem instances, such as in rescheduling. The RL agent gradually learns to make better decisions by leveraging patterns in the problem structure which could lead to faster and more efficient optimization in dynamic scenarios like adjusting timetables in response to delays or incorporating new trains into the schedule.

Railway Passenger Flow Monitoring and Prediction in Stations and on Platforms Using Curve Estimation Methods for Energy-Efficient Railway Systems

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The rapid growth of urbanization and increasing demand for railway transportation necessitate advanced monitoring and prediction systems for railway passenger flow to optimize passengers' capacity utilization and ensure smooth operations. This study proposes research methodologies consolidating curve estimation techniques between passenger flow capacity and real-case dwell time variations for effective railway passenger flow monitoring and prediction in stations and on platforms with a contribution to energy-efficient railway systems. The purpose is to accurately predict passenger flow under varying conditions, enhancing operational efficiency, reducing congestion, and improving passenger experience. A dual-track rail route was selected as a case study to assess the effectiveness of the developed model in real-world scenarios. For curve estimation methods, general and routine passengers' capacity data were employed to model the temporal variations of total passenger flow data indicated by Ministry of Land, Infrastructure, Transport and Tourism. Additionally, variations in real-case dwell times are analyzed their impact on energy efficiency to improve operational performance due to their influence on acceleration, braking, and scheduling for the double-track railway route line. The predictive capability of proposed models was validated by using historical datasets. The evaluation results demonstrate that the proposed methodology enhances better prediction accuracy than traditional statistical techniques such as linear regression. Suitable curve estimation methods were proposed as multi-selection options. Additionally, the study explores the spatial distribution of passengers across platforms, enabling more efficient scheduling, resource allocation, and energy-saving measures. The finding results provide practical applications for railway operators and policymakers in effectively managing passenger flow, mitigating congestion issues and optimizing energy consumption. The demonstrated effectiveness of curve estimation techniques in predicting train passenger patterns and optimizing dwell times supports future deployment in intelligent railway transportation systems, including multimodal transportation systems, to strengthen resilience and reliability and energy efficiency of railway operations and executions.

Improving timetabling through reliable description of infrastructure data using IDX4rail standard

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Today, rail- and tramway parties are siloed from each other even though there already exists and successfully operates rolling stock able to go on both e.g. Karlsruhe Stadtbahn. Consequently, there are two data standards for rail: railML® for the heavy rail and IDMVU (Infrastruktur-Daten-Management für Verkehrsunternehmen) for light rail- and tramway data. The aim of IDX4rail project is to facilitate data integration and transformation utilizing state of art technologies by proving a common language for all rail-based ways of transport. The new IDX4rail standard being developed in the project is to facilitate data integration and transformation utilizing state of art ontological technologies to allow for the incorporation of natural language constraints into the model and their automated validation. Within this project funded by the German Ministry of Transport and Digitization (BMDV) eight data exchange use cases have been developed: track network, functional assets, track geometry, asset status representation, schematic track plan, maintenance data, network statement, and change management, e.g. “track network” use case is a description of the railway (tram-) network utilizing RailTopoModel. These use cases are complementary, e.g. “Functional assets” builds on the top of “Track network” adding functional infrastructure or “Track geometry” builds on “Functional assets” adding necessity of topology and geometric coordinates of the tram- railway tracks. Based on grounding the requirements for IDX4rail standard, the conceptualization, formalization and implementation of a common language for all rail-based ways of transport will be performed. When timetables need to be tested, the railway network had to be entered formally in terms of distances, gradients, curves. Infrastructure Managers may be interested in improving the performance of railway infrastructure. What happens if a signal is removed? Specialised designers of simulation software designed to answer such questions would find it highly helpful when uniform data are available to answer such what-if questions.

Railway Track Gauge Measurement Based on LiDAR and Camera

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The automation of railway inspection and maintenance can significantly reduce the operating costs of railway companies. With the development of machine learning technology, introducing machine learning algorithms to analyse railway detection data has become a new approach. LiDAR can generate precise location clouds, and it can be used to detect the shape of railways. We can calculate the gauge between two tracks based on the information of the railway tracks and the coordinates of the location where the LiDAR is placed. However, a major drawback of this method is its susceptibility to interference from vegetation on the railway, resulting in significant fluctuations in the gauge results. To address this issue, we installed a camera near the LiDAR and used a CNN based deep learning network to detect the presence of vegetation and locate their positions. We use ResNet50 as the backbone to train a classifier that can recognize vegetation. To achieve better classification performance, we choose to fine-tune pretrained ResNet50 and modified the structure of the last layer to adapt to the vegetation detection task. We used weakly supervised training methods, using fewer labelled images and more unlabeled images. After fine tuning, the AUROC of this model can reach 0.98 and effectively generate CAM (Class Activation Map) to indicate the location of vegetation in the image. Our method successfully eliminates the interference of vegetation on LiDAR data, allowing us to detect track gauge more accurately. This method will help railway companies automate gauge detection, reduce the complexity and time of railway maintenance, and lower the maintenance cost of railway tracks.

Non-discriminatory principles applied to rail traffic management in case of long disruptions and reduced capacity.

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Non-discriminatory principles are one of the prerequisites for managing rail networks and their traffic. Recent studies have identified useful KPIs for managing non-discrimination between stakeholders, which consider train delays of different train operators or passengers' delays according to their destinations. These studies are however limited to rescheduling conditions where the infrastructure capacity is still able to support the planned timetable. In those cases where reduced capacity does not allow the planned timetable to be operated, the current KPIs are not enough to represent the operating restrictions and additional conditions must be found. In this work, we consider these cases, and we assume that this kind of capacity reduction will last for more than 1 day (e.g. incident + repair time). Specifically, decisions on train cancellations must be taken and thus train cancelations must be explicitly introduced in the generation process of disposition timetable, to find the right set of trains that results in a non-discriminatory choice for both train operators and passengers, and aligned with the rules set by the authorities. Moreover, a loss of infrastructure capacity can lead to rerouting and longer travel times. Considering passenger trains, this can complicate the travel chains of passengers and the connections with the trains not affected by the disruption. All these aspects are considered in this work, which proposes an innovative approach to set non-discriminatory conditions for rail traffic management in case of reduced capacity and long disruptions (>1 day), when a disposition timetable must be produced. The case study of the Gotthard Basis Tunnel incident (August '23-September '24) is considered to support the discussion and the conclusions. This work is based on the activities of a research project with the SBB funded by the federal innovation agency Innosuisse, and preliminary results and the current status of the work are presented.

FRI-2-A: BREAK + POSTER SESSION

Time: Friday, 04/Apr/2025: 11:00am - 12:00pm · *Location:* POT/168/S

The pursuit of statistical validity in analysing rail network enhancements, and the consequential development of the Traxim rail network modelling tool.

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The challenge of planning for growth and performance improvement on the Australian interstate and Hunter Valley coal networks catalysed a decades long pursuit of a practical tool to support quantitative analysis of competing rail network enhancement options. While inductive approaches to analysing performance, such as the International Union of Railways capacity calculation methods, offer considerable insight and provide a platform for hypothesis testing, they are unable to adequately synthesise the many complex interactions present in a large, heterogeneous rail network. The desirable complement to the inductive approach is to generate a population of perturbed timetables to give statistically significant performance outcomes for competing options for future infrastructure configuration and operational practices. However, the time involved in manually generating timetables, and the risk of systematic bias in a manual approach, demands a tool that can automate and objectify the process. Such a tool needs to be sufficiently macroscopic that it can generate viable timetables in a pragmatically short timeframe, while being sufficiently microscopic that it enables efficient and realistic replication of the many input variables that impact real-world operational performance. The authors have now advanced such a tool, Traxim, to a mature and commercially viable state.

Detailed Operational Timetables for Metro Rail Operation: A Case Study of Delhi Metro

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Timetabling in metro-rail operations is essential for efficient train movement and adapting to variable passenger demand. This study presents an integrated timetabling model that utilizes key operational data from line planning: short-turn ratios and rolling stock availability, to develop an operational schedule. Key challenges include managing headways across peak and off-peak transitions and addressing conflicts due to short-turn rakes and shifts between high-speed and energy-saving coasting modes. Our model deploys the full fleet during peak hours with minimized traversal times to achieve tight headways. For off-peak periods, it adjusts by reducing active rakes and increasing headway through coasting mode, conserving energy and cutting costs. During evening peaks, additional rakes are reintroduced, again focusing on tight traversal to meet demand. To prevent headway clashes, the model applies scheduling adjustments, especially for short-turn operations and speed changes, ensuring service continuity. After establishing the core timetable, start times are assigned to rakes based on backtracking from peak hours, and nighttime stabling is arranged. This approach enhances both service efficiency and resource utilization, offering a relevant solution for urban rail systems.

Enhancing single-track local railway operation: Conditional stops and improvement of robustness

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This article deals with the challenges and strategic improvements on a single-track railway line in Eastern Denmark connecting local urban communities with larger cities. Key concerns include the closure of smaller halts, timetable robustness, train punctuality, and infrastructure limitations. A 2009-2010 speed upgrade was only partially completed, resulting in an inadequate infrastructure that cannot support all planned changes to the traffic, like a new passing loop and closure of the smallest halts. To address performance issues, measures such as replacement of old rolling stock, conditional stopping, and dynamic use of passing stations has been implemented without using extra trains to operate the service. These efforts decreased dwell times significantly, leading to improved punctuality and reduced travel times for passengers. Despite these enhancements, the railway line's robustness remains unsatisfactory, with issues persisting at timetable-level and infrastructural inadequacies. Prospective solutions include further local investments in speed upgrades over timetable restructuring. Potential future developments contemplate a new timetable structure for ease of passenger use, extended services to the national rail network, and a new halt to support urban developments. The analysis in the article identifies conditional stopping as an efficient method to reduce running times and enhance punctuality but highlights the need for additional improvements to achieve desired robustness in railway operation. The overall focus is on optimizing the existing infrastructure and service without necessarily increasing the number of operating trains, which could incur significant costs.

A Framework for Integrating Passenger Parameters into Automatic Train Regulation Systems

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With the growing demand for public transport, railway stations often face challenges in managing passenger flow, leading to overcrowded platforms. Effective passenger flow management is crucial for ensuring safety, comfort, and operational efficiency. This study develops a framework for enhancing Automatic Train Regulation (ATR) by incorporating passenger parameters to regulate train headway and arrival timing at crowded and shared platforms. By demonstrating data such as passenger counts, train schedules, and platform occupancy, this framework aims to enable ATR adjustments, including modifying train schedules or regulating headways, to mitigate platform congestion. The proposed methodology focuses on developing a framework for adding passenger parameters into ATR system. Initial steps involve defining passenger-related parameters critical to ATR functionality, such as the volume of alighting and boarding passengers and platform density. The research identifies and assesses various data sources in Thai metro's system to determine data availability. The research also outlines operational strategies that have been proposed in existing studies. Pilot studies will develop this ATR framework using Alstom's train regulation system to evaluate the possibility of integrating this function into the system. The potential contributions of this research include a practical and scalable framework for incorporating passenger-centric parameters into ATR, providing a foundation for adopting this function to existing railway systems. Additionally, it offers insights into optimizing ATR for urban railway environments, enhancing real-time decision-making to improve operational efficiency and passenger experience.

A strategic planning of micromobility spaces for managing urban railway network disruptions

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The integration of shared micromobility and existing public transit system has been perceived as an efficient solution for improving first and last mile connectivity of the transportation system. In urban settings, the connection of micromobility trips with urban rail results in 5 to 20% (Frolich et al., 2024), which further requires directions for its improvement, mainly by analysing their spatial, infrastructure, and passengers' accessibility. Especially in the case of urban rail during disruptions, bridging with micromobility is a potential strategy to increase resilience. This study proposes a novel optimization model that determinates the location for placing micromobility services by maximizing their benefits to supplement urban rail system in the case of disruptions. The aim is ease the access, promptly respond as well as increase reaching the destinations. The proposed model has been tested on a middle-size city in Germany. The outcomes of the proposed work could be considered as one of the main directions for handling high passenger demand, and for moving towards eco-friendly mobility paradigms by shifting to more sustainable travel modes.

Fail to Board Optimization on Metro Networks Using Artificial Intelligence and a Digital Twin

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Subway operators face critical fail-to-board (FTB) issues, usually in highly centralized stations, leading to overcrowded platforms. Crowded trains prevent passengers from boarding, creating safety concerns such as a risk of falling and petty theft. A traditional approach to address FTB is to adjust train schedules at the beginning of missions and inject empty trains starting their service at the overcrowded stations. However, reducing FTB at these stops increases FTB at other stations, an important trade-off across the network. To tackle this issue, we developed a digital twin of a revenue-service metro system, using real-world partner's ticketing data to simulate various dispatch strategies and network conditions. Focusing on the central station (CS), which is the most affected by FTB due to the metro layout, we propose a combined optimization framework based on Deep Reinforcement Learning (DRL) and Genetic Algorithms (GA) to continuously optimize this trade-off across the entire network. Our method was evaluated against both the operator's manual solution and a well-known solver. The solver reduced FTB only at CS by 33% in 3 to 15 minutes of computation time depending on the network load. The GA achieved similar results (+/-0.1%) but reduced computation time to a steady 1 minute and optimized the entire network. The DRL solution provided comparable results, with a +2% difference, but required only 1 second to identify the optimal policy for the full network. While DRL sacrifices a small degree of accuracy, its near-real-time processing makes it invaluable for time-sensitive operations. The combination of GA and DRL offers a strong balance between computation time and optimization accuracy, optimizing the entire network rather than focusing solely on the central station.

Comparative Analysis of Observation Approaches in Multi-Agent Reinforcement Learning for Railway Scheduling and Operations

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Within the sector initiative Digitale Schiene Deutschland[1], a Capacity & Traffic Management System (CTMS) for highly automated planning and dispatching is being developed alongside other future technologies for the digitization of the rail system. The prototype CTMS leverages Multi-Agent Reinforcement Learning (MARL), with train agents interacting in a realistic railway simulation. A key challenge in this MARL approach is the effective processing of information on the state of the simulation environment in complex, multi-agent scenarios. This study focuses on optimizing observation strategies to overcome the curse of dimensionality in large railway networks. Initially, a local observation strategy targeted the immediate surroundings of trains, simplifying data processing but failing to capture the broader network dynamics. To address this limitation, we expanded our approach to include distant trains, utilizing pooling-based models that aggregate data regardless of sequence, ensuring permutation invariance while providing deeper insights into the complex dynamics of railway networks. Our results compare the local observation approach with the pooling-based approach in terms of scalability and result quality in realistic operational scenarios. The analysis demonstrates that while the local approach is computationally simpler, it falls short in capturing essential network-wide interactions. In contrast, the pooling approach effectively addresses permutation dependency, delivering higher-quality outcomes, particularly in complex, large-scale settings. This contribution advances the application of AI in railway scheduling and control, showcasing innovative solutions to manage the complexity of information in large-scale, multi-agent systems. Our findings are instrumental in developing scalable, efficient AI-based strategies for effective railway traffic management.

[1] https://digitale-schiene-deutschland.de/en

Consideration of network effects in the determination of capacities in railway networks

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In the context of railway infrastructure, capacity is often defined as the maximum number of train journeys that can circulate on the considered infrastructure while maintaining a certain level of quality. The available capacity thus plays a decisive role in the long-term dimensioning of railway infrastructure. However, methods for capacity determination are usually limited to individual lines and elements of the node while interactions between the infrastructure elements are not being considered.

We introduce a mixed-integer program that comprises railway-specific constraints such as compliance with line capacities or a specified train mixture. Under consideration of these constraints, the developed model enables a network-wide calculation of capacities and can for example be applied to investigate the impact of changes in load or available capacity on the network and to determine residual capacities. The developed model is applied for different scenarios in order to analyze the extent to which the capacities of individual elements can be used under consideration of interactions. For example, we identify effects that can reduce the usable line capacity, including the partial single tracking of lines, the crossing and converging of routes in important nodes as well as the train mixture in the network. Further, the network size is increased successively for the investigated networks and the resulting changes are examined. This allows us to analyze the relationship between network size and computation time and to derive statements on the range of interactions between infrastructure parts. Our model represents a successful approach to determining network-wide capacities and can be used as a base for further research investigating bottlenecks, the impact of line closures or residual capacities for additional trains.

Data Interface for rail timetable construction and operational dispatching center

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Data exchange in the railway industry, especially in train planning, train control, and train simulation, is becoming increasingly complex and requires high data accuracy. RailML uses Extensible Markup Language (XML) as the basis for its data structure, enabling efficient data management and exchange between different systems. This study focuses on developing a tool that enables the conversion of RailML data exported from train scheduling software into Access Database format for use in train control laboratory simulation programs. This conversion is important because it allows for continuous data usage between the two programs, reduces errors, and increases operational flexibility. The main objective of this research is to develop a tool that can efficiently convert RailML timetable data into Access Database data, enabling interoperability between programs using different data standards. The research methodology consists of three experimental steps. The first step involves studying and analyzing the structure and content of RailML and Access Database data to understand the data requirements. The second step involves writing code to develop a data conversion tool based on this analysis. The third step is to test the tool to verify the accuracy of the data conversion. The results show that the developed tool can efficiently convert RailML data into Access Database format, enabling smooth integration with the train control laboratory simulation program and reducing errors from manual data entry. However, differences in the formats of the different various RailML versions pose challenges that require customization of the tool. This study proposes an effective approach to improving data management, promoting interoperability between timetable generators and train control laboratory simulation programs.

Optimized Short-Term Insertion of an Additional Train Into an Existing Timetable

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In railway operations, train scheduling is a complex and lengthy process that is required by both Infrastructure Managers (IMs) and Train Operating Companies (TOCs), months to years before implementing a timetable. However, short-term train insertion requests, especially for freight services, are often received within a week of the implementation. At SNCF, these requests are currently handled sequentially, through coordination between local and regional planners. While this approach may sometimes yield solutions, there is still a risk of rejecting requests that the IM could have fulfilled, if the problem had been addressed using global approaches. Thus, it is beneficial for the IM to design such methods, as this should help to optimize train scheduling and operations, through a better management of the infrastructure's residual capacity. Despite its relevance in improving the use of the railway infrastructure, this problem of residual capacity management has received relatively limited attention in the literature. The problem is mostly treated at the macroscopic level of infrastructure modeling, with applications on specific parts of a given railway network, usually a given railway line. This raises doubts regarding the level of applicability of the methods proposed in the literature to solve the problem of inserting one or several trains in real-life railway timetabling. Based on this conclusion, the French IM, SNCF Réseau, proposes to study the problem at a more detailed level of infrastructure modeling, by exploring simulation-based methods that are applicable not only to a single railway line, but also in complex networks. This poster aims to describe the problem, position it in the literature and introduce a first time-expanded graph approach proposed by SNCF Réseau. Then, a station track reallocation algorithm is proposed, which aims to insert an additional train by unlocking more short-term train paths through minor acceptable adjustments to the existing timetable.

Learning for RECIFE-MILP: a Parameter Configuration Perspective

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RECIFE-MILP is a railway traffic management algorithm that focuses on the rerouting and rescheduling of trains in response to perturbations. This algorithm relies on the solution of a mixed integer linear programming (MILP) model. The underlying framework of RECIFE-MILP encompasses numerous configurable parameters, which can significantly influence performance but are challenging to tune manually. Consequently, automatic parameter configuration has emerged as a need to achieve good performance. Currently, several advanced tools for automatic parameter configuration exist, among which IRACE stands out for its effectiveness in identifying good configurations for algorithms based on sets of problem instances. In this paper, we present an experimental study on the parameter tuning of RECIFE-MILP using the IRACE tool. We categorize homogeneous instances into subsets and execute IRACE separately on each subset to derive the best configuration tailored to each instance class (specialized configuration). Additionally, we apply IRACE to a heterogeneous set of instances to obtain a generalist configuration. The test results indicate that each specialized configuration is steadily the best one for instances similar to the ones used for the tuning; moreover, when compared with the generalist configuration, it exhibits superior performance in these instances. These results reveal that there are instance features which can be linked to the effectiveness of some configurations. Subsequently, we investigate how different parameters affect RECIFE-MILP's performance. Our analysis reveals that the importance of some parameters associated with the branch-and-bound process rank high. This insight lays a foundation for integrating machine learning approaches with branch-and-bound methodologies within RECIFE-MILP, to learn and exploit the best configuration when solving each instance.

Learning to Reduce Railway Traffic Management Problems

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Railway traffic management (RTM) involves the adjustment of train timetables that have become infeasible due to unforeseen disturbances or disruptions. Under real-life conditions, rescheduling decisions need to be made quickly and frequently. However, traditional state-of-the-art optimization algorithms suffer a loss of performance when they are applied to complex instances and large-scale railway networks. As solving RTM problems are NP-complete combinatorial optimization tasks, computation time rises dramatically with the complexity of the problem under consideration. While decomposition approaches and novel rescheduling models based on Artificial Intelligence have been investigated in the literature to improve real-time performance, they have not yet been able to consistently outperform traditional optimization algorithms. To address these computational challenges, we propose a supervised Machine Learning (ML) problem reduction framework designed to reduce the scope of complex RTM problems by applying so-called scopers. These scopers learn from labeled problem instances, which are pre-solved by a benchmark rescheduling model, to predict the core sub-problem including only the critical trains, network areas, and time periods that are required for high-quality rescheduling. We develop several scopers based on artificial neural networks and tree-based ML classifiers. For unseen instances, the trained scopers provide key information to an existing rescheduling model. As a result, this pre-processing step is expected to significantly reduce computation time, particularly for complex RTM problems. The effectiveness of the problem reduction framework is demonstrated using simulated disruption scenarios of a medium size station area. To evaluate scoper performance, we compare the computation time and decision quality of the benchmark rescheduling model used for training of the scopers – both based on the reduced and the full problem. Finally, the best performing scoper is selected.

Passenger Origin-Destination Matrix estimation using Wi-Fi on board

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Wi-Fi onboard trains enhance the travel experience of passengers, who stay online during their trip. For operations, routers are monitored online using MQTT as a machine-to-machine network protocol, the per- sistence of data enabling off-line and online network analysis. Our approach uses onboard Wi-Fi routers to follow passengers in trains (anonymously as addresses are hashed at the source), using passive scan- ning that gathers all MAC addresses pinging the routers and active scanning that gathers all MAC addresses connected. Using that signal, we model passenger count, but more importantly we compute accurate Origin-Destination (OD) matrixes online. Computing an OD matrix is impossible for most railway networks as sensors only provide IN/OUT counting information at doors and ticketing often does not include check-out information. Operators usually get them offline from costly manual surveys. Modeling performance depends on the quantity of passengers represented accurately by the signal. Active scanning accounts reliably for around 15% of people on board. Our approach includes a novel fine-grained capacity to denoise passive pings data that improves passenger representativity. Around 80% of MAC addresses have an irrelevant behavior, including 60% of devices pinging only once per day in the network (pings at stations, when a train crosses a road, ...). Following all pings of a device from its departure station to its arrival enables excluding abnormal behaviors and outliers. The resulting denoised passive data represents around 30% of people on board. Validation is done by training a Random Forest model to predict the number of passengers on-board and comparing it to a noisy ground truth conducted by manual on-board counting. The performance reaches 0.68 and 0.84 of R2 and a Pearson correlation coefficient, respectively, on out-of-time evaluation data, showing a promising relationship with manual counting. Further work includes deploying counting sensors to accurately evaluate against a precise ground-truth.

Reinforcement learning approach for train rescheduling: A review and future directions

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Critical infrastructures such as railways are expected to operate efficiently due to their essential role in society. In everyday railway operations, delays are inevitable; while minor delays can often be compensated within the network, major delays that can be caused by disruptions may require the timetable to be rescheduled. Currently, much of the existing literature focuses on operations research or heuristic approaches to minimize delay propagation in train timetable rescheduling (TTR), while recent studies are exploring alternative data-driven methods, including reinforcement learning (RL). Although the integration of RL in TTR has gained popularity in recent years, existing solutions often face challenges in real-world railway operations. This research aims to critically examine the existing RL approaches for TTR covering the main characteristics including considered assumptions, level of details, scalability as well as the key benefits and limitations. Further, we provide recommendations for future research, offering insights into how RL-based methods can be developed to address real-world constraints, guarantee feasibility, and improve scalability.

Size matters: Adapting HEROS to ensure usability in large flat yards

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The optimization of shunting processes is crucial for the efficient operation of industrial railways and yards in freight transport networks. Our heuristic algorithm HEROS (Hybrid of Evolutionary and Reinforcement Optimization for Shunting) is a multi-stage optimization method specially designed to optimize flat yards. It combines key principles of evolutionary algorithms and reinforcement learning. The core idea of HEROS lies in an effective combination of exploration and exploitation of the solution space, based on which a graph representation of possible shunting operations is determined. More precisely, we start with an opening heuristic to determine an initial solution, thereby establishing a preliminary path within the graph as an upper bound. The exploration phase extends this graph incrementally by adding new nodes and edges that correspond to new shunting operations and new states of the yard, respectively. During the exploitation phase, HEROS searches for new paths through the extended graph and thus improves the objective value. The exploration and exploitation phases are alternated until a previously defined termination criterion is met. The optimal solution is then obtained from the constructed graph using an efficient shortest-path algorithm. In previous studies, HEROS has shown promising performance, particularly in smaller yards, where the optimization also shows a high level of robustness and reliability. Although our method quickly finds an initial solution, the improvements made during its exploration and exploitation phases decrease with increasing problem size. To ensure the usability of our algorithm also for large-scale instances - which contain more tracks and longer trains - we conduct an in-depth investigation of the graph-creating process to identify its current limitations. Based on our findings, we will refine the algorithm's exploration phase and demonstrate its scalability through an experimental study.

Temporal Criticality in Railway Operation

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The value of railway services for society is inter alia defined by their timeliness. Ensuring timeliness, operators usually integrate running and dwell time supplements or additional headway into their schedules to dampen effects of disturbances causing delays. However, operators must trade off operational efficiency and these buffer times. Recently timeliness criticality, a phenomenon of schedule-based systems leading to delay cascading, was described theoretically and tested with two simple real-world examples (Moran et al. 2024). They find that schedule-based systems exhibit a critical buffer between related events in which at least two agents are involved. In this context, buffer generally refers to a time value between two related events. The system operates in two distinct phases below and above this critical buffer, resulting in the system dynamics differing widely in terms of delay propagation. This study analyses timeliness criticality in railways. Railways are schedule-based systems where large parts of the schedule are centrally coordinated as well as public (compared to for example supply chain networks). Therefore, railways provide a unique opportunity to analyse the phenomenon of timeliness criticality in a complex, real-world example. Understanding the timeliness criticality of a specific railway network furthermore provides relevant insights for industry, for example the critical buffer time of a system. We analyse timeliness criticality in a case study of an isolated railway network in Switzerland of which we possess schedule, infrastructure and crew as well as vehicle rotation data. The goals are to verify the existence of temporal criticality on a real-world example. We are further aiming on addressing open questions of the phenomenon for example on heterogeneous composition of temporal buffers and provide industrial insight by for example calculating the critical buffer time or identifying typical delay avalanches.

Moran, J., Romeijnders,... (2024). Timeliness criticality in complex systems. Nature Physics, 20(8), 1352–1358. https://doi.org/10.1038/s41567-024-02525-w

Spatiotemporal Multi-Graph Neural Network for Metro Passenger Flow Forecasting(ST-MGNN)

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As urban rail transit networks continue to expand, station operations are encountering a growing array of challenges. Striking an efficient balance between transportation supply and demand has emerged as a critical issue. Short-term passenger flow forecasting plays a vital role in providing real-time traffic information, which supports station operations and empowers passengers to make informed travel decisions. However, existing forecasting methods often fall short in capturing the spatiotemporal dynamics of passenger flow within the network. Most current approaches predominantly rely on historical data from the temporal dimension, while spatial features frequently overlook the dynamic inter-station relationships from an operational perspective. To address these issues, we propose a Spatiotemporal Multi-Graph Neural Network (ST-MGNN) to extract temporal features from historical data and capture dynamic spatial dependencies among stations. The model constructs static and dynamic graphs, including travel time, functional correlations, pattern similarity, and dynamic origin-destination (OD) distribution graphs, where the dynamic OD distribution graph based on Gaussian mixture clustering captures temporal OD variations. The model integrates graph convolutional networks and graph attention networks to extract inter-station correlations from graphs, while a gated convolutional neural network captures short-term and long-term temporal features of passenger flow sequences. The model is validated using AFC data from Chongqing Rail Transit through comparative and ablation experiments under the time interval of 15, 30, and 45 min. Compared to the baselines, our model effectively captures peak passenger flow trends and demonstrates robust performance across varying passenger flow levels. Results show that this model yields the best performance compared with nine other models. In terms of the root-mean-square errors, the performances under 15 min has been improved by 9.41% to 25.87%. Ablation experiments further validate the effectiveness of incorporating the travel time graph, functional correlations graph, pattern similarity graph and dynamic OD distribution graph.

Smart Troubleshooting of TCMS Events Data for Improved Decision-Making in Rolling Stock Maintenance

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Effective prioritization of daily railway maintenance inspections is crucial for addressing unforeseen degradations in rolling stock components and hence for meeting availability requirements. Thus, swiftly identifying potentially degraded assets and minimizing troubleshooting time is essential. Operational status information from key rolling stock subsystems, such as brakes, doors, and air conditioning, can be extracted by analyzing logs from the Train Control and Monitoring System (TCMS). However, with thousands of events generated per train daily, manual analysis becomes impractical. The proposed method generates a prioritized list of trains requiring inspection for potential repairs using only daily aggregated data, eliminating the need for additional context such as mileage, location, or timestamps. By examining event occurrences across the fleet over time, the method identifies anomalous bursts—sequences of unusually high values compared to baseline levels, which are derived from historical data and fleet comparison. If the occurrence of a specific feature of interest increases significantly, the likelihood of transitioning from a baseline state to a bursty state also rises. The method calculates the probability of an observation being in either state using a data-driven risk criterion, determining the intensity and duration of bursts to rank trains accordingly. The method has been developed and tested on data collected from Alstom fleet in revenue service. The capability to consistently detect unusual burst events has been proven. The method has been integrated into existing Alstom's decision-making tools to aid in scheduling maintenance interventions. The impact on rolling stock availability and on troubleshooting time is currently under evaluation.

Multi-Agent Pathfinding for Railway Routing

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Research in railway operations has mostly focused on operations research methods. However, these real-world problems have a state-based nature, which makes them very suitable for AI models, such as the Multi-Agent Pathfinding problem, where agents move in a grid and need to be routed from their start to their goal location without colliding with each other. The core aspect of problems like train shunting and train dispatching is routing, which is often not the main focus of current mathematical formulations. Therefore, we apply the state-of-the-art algorithms to the railway problems of shunting and dispatching and study their usability for routing trains. The Multi-Agent Pathfinding problem is often solved with one of two algorithms: conflict-based search (a two-stage algorithm detecting conflicts between individual paths and using A* search to find new conflict-free paths), and branch-cut-and-price (a linear program adding cuts (row generation) based on problem-specific constraints, and finding new paths to be selected that satisfy all constraints using a pricer). We modify these algorithms to include more railway details. First, we allow for the matching of train units (i.e., ensure the necessary train units of a certain type are available for departure) by specifying goals for agent (type) groups instead of single agent goals. Moreover, we add goal sequences for servicing stations and agents of different sizes, and we study specific aspects of the railway infrastructure to exploit in the algorithm. Finally, we show the use of Multi-Agent Pathfinding solvers in different railway settings and analyze the conditions for success.

Payload maximisation on single-track railway lines

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The ambitious railway share increase sought in the freight sector requires defining enough train paths to fulfil the forecasted demand. The development of the European railway network to fit 740 meter long freight trains is a challenging task, especially on single-track lines. The lower availability of passing loops for these long, high payload, mostly container trains sets a significant scheduling restriction with respect to shorter freight trains. This generates a trade-off between scheduling more short trains vs lesser number of longer trains considering corridor capacity. So far, current freight timetabling research for capacity maximisation has mostly focused on fulfilling operator's requests by inserting individual trains in a given timetable. This paper proposes a new mathematical optimization model for the single-track timetabling train problem (TTP) considering a heterogeneous fleet for freight services and the different infrastructure constraints for each type of train. The formulation of the model is expressed in terms of a multi-stage job shop scheduling (JSS) problem. Given a fixed passenger timetable, freight train paths are determined simultaneously while the total payload is maximised. The proposed model is demonstrated on several realistic instances with different grades of abstraction. And finally, we present its potential for further development.

FRI-2-B: BREAK + POSTER SESSION

Time: Friday, 04/Apr/2025: 11:00am - 12:00pm · *Location:* POT/161/S

Back for Good - Re-Optimization of Rolling Stock Rotations

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There are manifold circumstances that lead to disruptions of railway timetables. All components, i.e., vehicles, crews, infrastructure, and passengers of the rail system must smoothly work together in a coordinated manner. However, construction sites, strikes, shortages of employees, vehicle breakdowns or capricious weather are common reasons for major deviations from the original or published timetable. In Germany the headlines of the press report that DB needs to adapt the timetable up to 3 million times within the year 2024. Even more they cite internals that the timetable is not scheduled anymore, it is only estimated. This is obviously in deep contrast to the progress and innovation which comes from digitization and automation in the age of the AI revolution. Bringing new technology in production is a major challenge itself. The focus of this paper is to present a mathematical rescheduling optimization approach based on Borndörfer et al. (2017) and its realization in R-OPT in order to support dispatchers in IVU.RAIL in their daily business. We provide a discussion of the re-optimization concept and main differences between planning and dispatching of rolling stock. Moreover, we present first computational results for show cases based on real world data.

Advanced Modelling of Energy Losses in Railway Vehicles for Optimized Operational Efficiency

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An established method from automotive research for optimal traction force distribution in distributed drives to enhance efficiency is applied to railway vehicles. To achieve this, a digital twin of the drive train is implemented that accurately considers the operating point and temperature-dependent losses of all components. The modeling and optimization process is derived and explained in detail. By optimizing the distribution of traction force among parallel drive trains, efficiency improvements can be achieved across a wide range of operating points. Particularly for low absolute traction forces, the optimization shows a significant potential with efficiency gains of several percentage points. The optimized method is compared to existing operational management using a realistic scenario for local transportation applications. Overall, the total energy demand can be reduced by nearly one percentage point. Through the analysis of temperature profiles of critical components such as IGBTs, the impact of the optimized operational management on component lifespan can be estimated.

Advancing reliability measures: a revised KPI framework for frequency-based metro system

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This research examines the efficacy of traditional Key Performance Indicators (KPIs) in frequency-based transportation systems, specifically focusing on the Copenhagen Metro. Existing metrics, such as Service Availability (SA), are limited as they primarily evaluate the frequency of station departures without addressing broader service quality aspects, such as punctuality, travel time, and responsiveness during operational shocks. This study introduces a novel KPI framework designed to provide a more comprehensive assessment of metro service performance. The proposed KPI framework integrates time-specific metrics such as departure production deviation, complete trips deviation, and punctuality indices, which are crucial for evaluating the real-time effectiveness of service delivery. In addition, we incorporate advanced variance measures like the standard deviation of delays and headway relative deviations to gauge the consistency and reliability of service intervals, which are vital for effective traffic management and operational planning. Utilizing a data-driven approach, this paper examines daily operational data over 6 months in 2023 to explore the relationship between these new KPIs and service performance. A correlation matrix between daily values of the KPIs shows the interdependencies between different operational aspects. The analysis includes a longitudinal investigation of headway stability and running time variations at individual stations and across the network. Eventually, a comparison of the ranking of operational days according to the different KPIs highlights the stability of “bad days” across different statistics, whereas the identification of the “best days” depends heavily on the specific measurement utilized. By suggesting a shift from mere frequency assessment to a multivariate evaluation framework, this research contributes to the strategic planning and enhancement of high-frequency public transport systems. The findings advocate for the adoption of more refined KPIs to improve transit management practices, aiming to meet the complex demands of modern urban environments while enhancing passenger satisfaction and overall system reliability.

Assessing Accessibility of Public Transport Using Real Time GTFS Data

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The analysis of accessibility is important for understanding the availability of public transport (PT). Typically, timetable data is used to calculate the accessibility of PT. Real-time data is not commonly implemented but could be used to better assess the availability of PT. The availability of PT is an important factor in describing the continuous operations of PT without disruption or delay. To compute the variance of accessibility due to disruption or delay of PT, real-time assessment of accessibility can provide a better understanding of the differences compared to scheduled accessibility. To calculate this, we assess real-time accessibility in cumulative opportunity measures using real-time general transit feed specification (GTFS RT) trip update data and OpenStreetMap (OSM) street network data. The GTFS RT data feed is stored in the application programming interface (API), where this data is regularly updated at a continuous interval. We collect the trip update data every 10-minute intervals in protocol buffer (.pb) format and combine them for a whole day in a comma-separated (CSV) format. We create a GTFS RT feed combining those trip update data. To build a real-time accessibility model, we selected open-source tools such as Open Trip Planner (OTP). We will create a map integrating with GTFS RT data and OSM data. Travel time origin-destination (OD) matrices will be made based on OSM and GTFS RT data. Several isochrones on 30, 60, 90, and 120-minute travel times for the selected city will be made. We will compare the deviations of accessibility on both schedule and real-time data. Real-time accessibility is a more precise approach for better public transport planning to identify disruptions or delays, and it can assess the reliability of PT.

Automating Algorithm Generation for Rescheduling with Generative AI

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Railway operations require adaptive and fast modeling for rescheduling under changing environments and requirements, yet current practices often involve skill-intensive and time-consuming manual definition and formulation of optimization models, e.g., during disruptions. We propose an autonomous workflow that uses large language models (LLMs) to automatically formulate optimization models from textual descriptions, i.e., an existing scientific publication. Our agentic approach includes LLM-driven text deconstruction and retrieval augmented generation (RAG) to preprocess the input. Subsequently, multiple LLM instances formulate an optimization model based solely on the syntactic description and compare it with the model formulation of the origin document. We tested the proposed workflow on several rescheduling publications, both well-known and recent, and therefore unlikely to be included in the training data of the LLMs. To evaluate the results, we applied common quality indicators from operations research, software engineering, and text complexity to both the original model formulations from the paper and the LLM-generated formulations. The results showed that LLMs can facilitate rapid prototyping of optimization model elements and provide creative alternatives, but with limitations in repeatability and no guaranteed functionality after the first shot. This methodology can be considered a blueprint for rapid prototyping in the research and development of mathematical optimization programs, enabling scalable and rapid optimization models in rescheduling and other areas subject to changing environments and requirements.

Employee Satisfaction and Wellbeing in Railway Crew Rostering

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We consider a crew rostering problem from the railway industry. In crew rostering, which is part of crew planning, a feasible schedule for each driver is constructed such that the anonymous duties that were created in the prior crew scheduling process are covered. We study the specific case of a railway operator. Rostering problems can be cyclic, which means that a group of employees works according to the same roster: Each crew member starts at a different position, usually a row of the roster, and cycles through the roster such that all duties are covered. In non-cyclic or personalized rostering, an individual roster is generated for each employee. Crew satisfaction aspects are becoming increasingly important since it is very difficult to recruit new drivers, and keeping existing personnel is very important. The quality of a roster, i.e., the placement of duties, the duration of rest periods, and the placing of consecutive days off, greatly impacts driver satisfaction. We propose an integer programming model to solve the problem. Different versions of the cyclic problem were studied. The base model considers legal constraints and company regulations. This model is further extended to include aspects of crew satisfaction, such as forbidding isolated duties or limiting the number of consecutive working days. The objective consists of overtime minimization. We also included forward rotation, which means that each consecutive duty starts later than the previous one and hence ensures longer breaks and a more desirable roster. Finally, a comparison between cyclic and non-cyclic crew rostering was carried out. In the computational study, we found that fixing free weekends and specific duties on weekends showed to be a promising strategy for reducing computation times. We further compared the different model versions and investigated different working-time models, as currently envisaged in practice.

Timetable optimization for high-speed trains with virtual coupling technology in a bottleneck area

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The high-speed railway is faced with increasing passenger demand, bringing a demand for higher transport capacity. In a bottleneck area of a high-speed railway line, there are a large number of cross-line trains with various speeds and stopping patterns, resulting in a waste of transport capacity. To increase the transport capacity, researchers proposed the virtual coupling technology, which enables trains to be coupled through vehicle-to-vehicle communication instead of physical connection. With virtual coupling technology adopted, trains can be coupled and decoupled during the running process, which can increase the transport capacity for trains with different stopping patterns and different speeds. In this paper, the train timetabling problem for high-speed trains under virtual coupling is investigated, where a mixed integer linear programming (MILP) model is proposed to minimize the occupation time of the timetable. If two trains are virtually coupled, their arrival times and departure times are identical, and they will occupy the same platform of a station. For two trains that are not virtually coupled, there is minimum headway between their arrival times and departure times, and there must be no conflict between their platform occupation. In addition, overtaking is not allowed to happen in the section between two consecutive stations due to the structure of the tracks. To denote these restrictions, binary variables are introduced to indicate the virtual coupling decisions, platform occupation and train sequence. The proposed MILP model can be solved by commercial solvers, e.g., CPLEX. Based on the data of Beijing-Shanghai High-speed Railway, a case study is conducted, demonstrating that the virtual coupling technology is able to increase the transport capacity.

The Coupling and Decoupling Simulation and Applicability Analysis of Virtually Coupled Trains

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Virtual coupling technology can enhance the operational flexibility of rail transit, effectively reduce train headway time and improve carrying capacity at busy stations. A simulation is conducted to analyze the motion dynamics of the decoupling and coupling processes of virtually coupled trains within the section. The simulation considers various influencing factors, including train parameters and safety intervals, using the China's CRH380 train as the research object. This paper compares the operational processes of trains under traditional moving block conditions and virtual coupling conditions, analyzing the impact of this technology on the carrying capacity of both sections and stations. The impact of virtual coupling technology on station carrying capacity under different scenarios is analyzed based on the results. The results indicate that when a station's departure capacity is saturated, the implementation of virtual coupling at the station can increase the number of trains dispatched within a certain period. By optimizing stopping strategies, virtually coupled trains can effectively decouple in sections. When the arrival capacity at a station or junction of railway lines is saturated, trains can be coupled in sections to enhance the carrying capacity of the station or the block post.

Study on the Energy Performance with Designing Maximum Traction Power and Gradients

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Energy saving in railways has recently become an important research topic. In addition to speed profile or timetable optimisation, operators are willing to explore the possibility of energy saving from the perspective of line design and train selection to reduce operating costs which can be represented by the maximum power of the train and the gradient of line respectively. Conventional studies have suggested that energy consumption will be minimized when a train follows maximum acceleration, cruising, coasting, and maximum braking strategy. However, gradients can significantly impact energy consumption, which provides a new way to train energy saving. This paper calculates the energy performance of trains with varying maximum traction power under different gradient conditions through an exhaustive search approach by dynamic programming. It was found that, under specific gradient configurations, reducing the maximum traction power may lead to a reduction in total energy consumption. To validate the applicability of this study, a section of a specific subway line was used as a case study. The results confirmed that optimising both gradient and traction power can indeed reduce total energy consumption.

Optimization of High-Speed Rail Express Service Plans under Intermodal Transport Mode

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The air-rail intermodal transport is an efficient and necessary choice for expanding the scope of high-speed rail express services. From the perspective of transportation organization, it is essential to optimize the service plans for express deliveries under the intermodal, specifically determining the train trips, flights, and corresponding spatial-temporal selections for each batch of express from the origin to the destination. This problem can be abstracted as a spatial-temporal path problem within a transportation network, where one type of intermodal transport for express deliveries is viewed as a state dimension. A three-dimensional spatial-temporal state network is constructed to depict the spatial-temporal paths and transfer mode selections for expresses.Various arcs are assigned costs representing transportation time and transfer time for the express. The capacity constraints of trains and flights are transformed into capacity constraints for task arcs, resulting in the formulation of a multi-commodity flow optimization model for high-speed rail express services under the intermodal transport mode. Using the Lagrangian relaxation algorithm, the capacity coupling constraints are relaxed, and the original problem to be decomposed into a shortest path problem for single batches of express within a multidimensional network.A dynamic programming method is employed to solve the sub-problem and obtain dual solution. A heuristic algorithm based on sub-gradient sorting is designed to obtain the feasible solution for the original problem.To compare the traditional solver methods with the Lagrangian relaxation.

Assessing the Integration of Urban Air Mobility and Public Transport in Saxony

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Urban Air Mobility (UAM) research primarily focuses on commercial services (e.g., airport shuttles, urban air taxis), user preferences, and optimal takeoff and landing sites, often treating UAM implicitly as transportation. However, little attention is given to its integration with public transport—including rail—or the benefits of classifying UAM in multiple ways (e.g., as technology, transportation, or infrastructure). This study addresses these gaps through an urban and regional development lens. This study introduces a pre-assessment framework for combining three interdisciplinary conceptual approaches for an assessment of the integration of UAM and public transport, including rail, at the level of urban and regional development: integrated infrastructure and spatial planning, infrastructure asset management, and regional economics. Based on this framework, the study formulates three hypotheses regarding the effects of UAM-public transport integration on welfare, sustainability, and business models. These hypotheses are tested at the state and community levels. The framework is demonstrated on public transport network in Saxony and assessed possibilities of eVTOLs being partially integrated with or partially replace existing public and private transportation systems. The initial results suggest that, on the state level, it may not be promising to introduce UAM in Saxony for welfare and sustainability reasons. At the same time, on the community level, the integration looks promising for some communities based on a multi-criteria decision analysis.

Research on Train Group Operation Control Method for Shortening Station Headway Time

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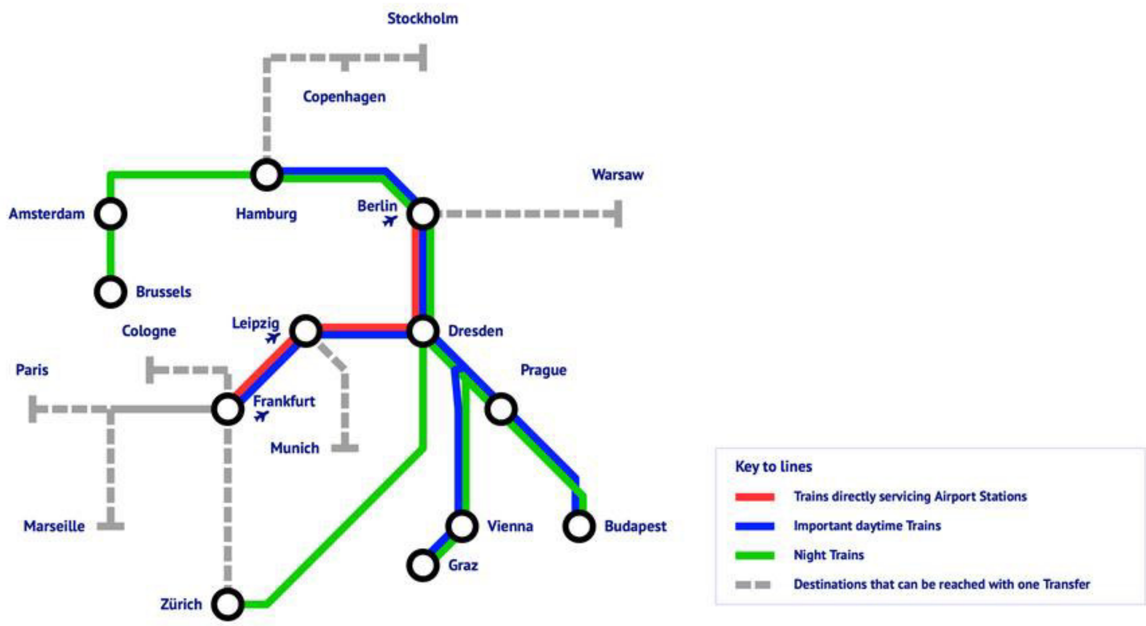
As a determining factor of railway capacity, the station headway time is influenced by both the running speed and braking distance of the trains. When the running speed increases, the time taken to traverse the same length decreases, while the braking distance increases. A motion model for trains is established in this paper. The impact of the running speed before entering the station on the headway time is analyzed and the optimal entry time based on the shortest headway time is determined. A case study is utilized to simulate two trains operating in a tracking mode, where the following train reduces speed in advance during the entry process of the leading train to ensure it arrives at a reasonable location at the optimal entry timing. The results demonstrate that early deceleration of the following train can effectively reduce the station headway time. Finally, a simulation involving ten consecutive trains is conducted to validate the applicability of this method for train groups.

Useful Information

How to get to RailDresden 2025?

As RailDresden is a conference about railroad engineering, we believe that we should be leading by example and attend the conference by train. Dresden is well-connected and accessible by national high-speed train as well as international long distance or night trains.
All of Germany's important cities and most cities in neighboring countries can be reached easily by train.



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ICE high-speed trains run bi-hourly to Frankfurt via Leipzig and Erfurt.

EC international trains run bi-hourly to Hamburg via Berlin and to Prague. Budapest is served transfer-free once daily.

The Euronight and Nightjet trains run between Dresden and Vienna, Budapest, and Graz every night.

Three times weekly, European Sleeper operates night trains from Brussels and Amsterdam to Dresden.

Visit Dresden

Dresden is beautiful! Classic meets modern, tradition kisses the future. But above all it means: Open your eyes and don't stop marvelling. Of course, you have to see the Semper Opera House, Zwinger Palace and Frauenkirche. But there is so much more! Look forward to exciting insights into over 800 years of history, a lot of the present and a whole lot of the future.

Highlights in Dresden Elbland that you simply have to see:

Church of Our Lady:

This is what the most beautiful baroque looks like. The Church of Our Lady (Frauenkirche), a masterpiece of European architecture. Built between 1726 and 1743, destroyed in the Second World War – and reconstructed after German reunification thanks to an international fundraising campaign – the church, which was reconsecrated in 2005, now stands for peace and reconciliation. Experience Dresden's landmark! >> more information!

Dresden Zwinger:

Augustus the Strong used the central square primarily for pompous celebrations – inside, he presented his art treasures, the basis of the later collections. Built between 1709 and 1728, the Dresden Zwinger is pure late Baroque. The former fortress houses museums such as the Mathematical-Physical Salon, the Porcelain Collection and the Old Masters Picture Gallery. Definitely worth a visit! >> more information!

Semperoper:

With a worldwide reputation: for music lovers, Dresden equals the Semperoper. They are not entirely wrong. See for yourself and experience one of the many top-class performances in one of the most beautiful theatres. And look forward to the typical sound of the Sächsische Staatskapelle, a trademark of Dresden for over 470 years. >> more information!

Dresden Residence Palace:

The Dresden Residence Palace, an impressive Renaissance building in the old town of Dresden, is one of the most important cultural sights. It served as the seat of the Dresden court and as the residential palace of the Saxon electors and kings. Today, the Residenzschloss houses one of the largest and most important museum complexes in Europe – the Dresden State Art Collections. The palace's collections are invaluable and include an enormous number of works of art and historical artefacts. A highlight is the world-famous Green Vault, which is one of the most precious treasure chambers in the world. >> more information!

Kunsthofpassage – the hidden jewel of the Outer New Town:

Discover the magic of the Kunsthofpassage in the Äußere Neustadt – a hidden gem that combines art, shopping and pleasure. This unique passage was created over 20 years ago from the vision of bringing old backyards to life. Each courtyard tells its own story through creative façade designs. Restaurants, cafés, charming shops and artists' studios await you here. Enjoy culinary delights, browse in small shops and immerse yourself in the special atmosphere. A meeting place for art lovers, connoisseurs and the curious who want to experience the best of culture and shopping. >> more information!

Vineyards in Saxony

Saxony is the most northeastern wine-growing region in Germany. Our wines are favored by the influences of the continental climate prevailing in the Elbe valley. You are planning to visit some of Saxony's famous vineyards? Here are our recommendations:

Schloss Wackerbarth

Tradition and origin. Schloss Wackerbarth's winemakers cultivate 17 grape varieties on an area of 90 hectares, making Wackerbarth one of the largest wine estates not just in Saxony but also in Germany. >> more information!

Hoflößnitz

Discover wine culture since 1401! >> more information!

For any further information and inspiration please see here.

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The RailDresden 2025 conference is organised by The International Association of Railway Operations Research (IAROR), the Chair of Transport Services and Logistics of Dresden University of Technology, the Chair of Railway Operations of Dresden University of Technology and Rail.S e. V.

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