Ref. Ares(2026)7706732 - 07/08/2026

Rail to Digital automated up to autonomous train operation

D32.5 – DATO capacity and impact simulations report

Due date of deliverable: 07/04/2026

Actual submission date: 07/04/2026

Leader/Responsible of this Deliverable: David Koopman – van Welij, ProRail

Reviewed: Y/N

Document status		
Revision	Date	Description
01	04/11/2024	First issue – 50% version Chapters 2-3
02	01/09/2025	Second issue – 90% version Chapters 2-4
03	19/03/2026	Third issue – for final internal review – 90% complete document
04	07/04/2026	Fourth issue – 100% / final version
05	06/05/2026	Fifth issue – incorporated feedback TMT review

Project funded from the European Union's Horizon Europe research and innovation programme		
Dissemination Level		
PU	Public	X
~~**SEN**~~	~~Sensitive – limited under the conditions of the Grant Agreement~~	

Start date: 01/12/2022 Duration: 42 months

ACKNOWLEDGEMENTS

This project has received funding from the Europe's Rail Joint Undertaking (ERJU) under the Grant Agreement no. 101102001. The JU receives support from the European Union's Horizon Europe research and innovation programme and the Europe's Rail JU members other than the Union.

REPORT CONTRIBUTORS

Name	Company	Details of Contribution
David Koopman – van Welij	ProRail	Author Chapters 3, 4, 6, 7; reviewer(all)
Thomas van den Berg	ProRail	Author Chapters 2, 3, 4, 5, 6, 7, 8, exec. summary; editor; reviewer(all)
Emil Jansson	KTH	Author Chapters 4, 5, 6, 7; reviewer(all)
Gerben Scheepmaker	NS	Author Chapters 3, 6, Appendix A; reviewer (all)
Miguel Letona Otaño	ADIF	Reviewer Chapters 2, 3
Álvaro López González	ADIF	Reviewer (all)
Simon Funke	DB Cargo	Reviewer (all)
Marcus Fischer	Knorr-Bremse	Reviewer (all)
Anders Lindfeldt	KTH	Reviewer (all)
Rowan van Pelt	NS	Reviewer (all)
Camiel Simons	NS	Reviewer Chapters 2, 3
Cor van 't Woudt	NS	Reviewer Chapters 2, 3, 4
Nils Olsson	NTNU	Reviewer (all)
Jesus Sánchez Domínguez	RENFE	Reviewer Chapters 2, 3
Joelle Aoun	TU Delft	Reviewer Chapters 2, 3
Monique de Wit	ProRail	Work Package Leader

Disclaimer

Funded by the European Union. Views and opinion expressed are however those of the author(s) only and do not necessarily reflect those of the European union. Neither the European Union nor the granting authority can be held responsible for them. The project FP2-R2DATO is supported by the Europe's Rail Joint Undertaking and its members.

EXECUTIVE SUMMARY

European railway systems are under increasing pressure to accommodate transport demand while maintaining attractive running times, punctuality, safety, and cost efficiency. In this context, Digital and Automated up to Autonomous Train Operations (DATO) techniques have emerged as a promising pathway to improve the performance and efficiency of railway systems. Consequently, a salient question becomes what exactly their potential capacity impacts are, and how to translate those impact estimates towards economic and financial effect estimates.

In response, this deliverable develops a comprehensive framework to assess how DATO technologies influence railway capacity and how these effects translate into economic and financial outcomes. Specifically, we develop a theoretical interface matrix that links changes in train traffic behaviour to capacity outcomes and, subsequently, to economic and financial value indicators, sorting impacts by the main stakeholder they accrue to, which include train operators, infrastructure managers, and society at large.

Note that the interface matrix is also applicable beyond the context of DATO and may be used as a reference document for any study into economic and financial effects resulting from changes in railway capacity. Since we consider this a major contribution to literature, we dedicate a large effort to its development and to the description of all relevant indicators and linkages within this document.

Next, the document describes tailored interface matrices for a range of DATO technologies, reflecting their distinct operational characteristics. For each technology, the report identifies the specific mechanisms through which train behaviour is altered and traces their implications for economic and financial value generation.

To illustrate its use and to measure the effects of selected DATO technologies (Automatic Train Operation, Hybrid Train Detection and New Generation Braking), we apply the interface matrices to DATO capacity simulation outputs from five use cases, including a dense mixed-traffic corridor in the Netherlands and four Swedish corridors with varying operational characteristics. We translate these results into a subset of economic and financial value indicators. Next, using the Business Case (BuCa) methodology proposed in Deliverable 32.1 (van den Berg et al., 2026), we present economic and financial effects by stakeholder for the Dutch case through a semi-quantitative value mapping approach.

The findings indicate that the selected DATO technologies can generate substantial traffic-change induced benefits. These benefits primarily arise from improved operational stability and reduced travel times. The largest share of value is found to accrue to society, reflecting gains in expected passenger time savings, mobility, agglomeration effects, and welfare-improving external effects resulting from an induced modal shift. Train operators also benefit through increased ticket revenues and slightly improved operational efficiency, while infrastructure managers experience comparatively smaller positive impacts. Overall, the results indicate that DATO technologies can significantly improve the performance and cost efficiency of the European railway system.

The economic and financial impacts from capacity changes because of DATO implementation can support policymakers with the decision which DATO techniques to implement. Moreover, showcasing sizeable and comprehensive economic and financial benefits may expedite the implementation of new technologies by encouraging stakeholders to expedite R&D and investment efforts, allowing Europe to maximize welfare and financial benefits by cashing them in as soon as possible.

Future work should focus on applying the interface matrix in studies that include detailed cost and revenue data from stakeholders, such that one can directly compare the capacity induced benefits with DATO implementation and operational costs. Also, as DATO technologies mature, the framework can be extended to more advanced operational scenarios and higher-fidelity simulations. Moreover, future work can apply the interface matrix beyond DATO, as it offers a general framework for assessing the impacts of any intervention affecting the spatio-temporal behaviour of trains.

In conclusion, this deliverable provides a structured approach to bridging the gap between railway capacity and economic evaluation. By linking capacity simulation outputs to quantified business and societal impacts, it supports evidence-based decision-making and strengthens the case for the continued development and deployment of digital and automated railway technologies in Europe.

ABBREVIATIONS AND ACRONYMS

ADS	Adhesion Determination Systems
ATO	Automatic Train Operation
BuCa	Business Case
C-DAS	Connected Driver Advisory System
CO	Coasting
CR	Cruising
DATO	Digital Automated up to Autonomous Train Operation
DAC	Digital Automated Coupler
DMU	Diesel Multiple Unit
Dxx.y	Deliverable number y of Work Package number xx
EETC	Energy-efficient Train Control (energy-optimal driving strategy)
EMU	Electric Multiple Unit
ETCS	European Train Control System
ERTMS	European Rail Traffic Management System
FP	Flagship Project
FDFT	Full Digital Freight Train
FRMCS	Future Railway Mobile Communication System
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
HTD	Hybrid Train Detection
Kdry	ETCS braking curve parameter for normal adhesion conditions
Kwet	ETCS braking curve parameter for low adhesion conditions
MA	Maximum acceleration
MB	Maximum braking
MC	Maximum Coasting (driving strategy)
MTTC	Minimum Time Train Control (minimal running time driving strategy)
NG Brake	New Generation Brake
OB	Onboard
NLP	Nonlinear Programming
PMP	Pontryagin’s Maximum Principle
R2DATO	Rail to Digital automated up to autonomous train operation

RBC	Radio Block Centre
RMS	Reduced Maximum Speed (Max Cruising driving strategy)
RTTP	Real Time Traffic Plan
TMS	Traffic Management System
TPE	Train Path Envelope
TS	Trackside
UIC	International Union of Railways
WP	Work Package

TABLE OF CONTENTS

Acknowledgements 2
Report Contributors 2
Executive Summary 3
Abbreviations and Acronyms 5
Table of Contents 7
List of Figures 10
List of Tables 12
2 Introduction 14
3 Railway Capacity to Business Case – an Interface Matrix 16
3.1 Capacity Building Blocks 18
3.1.1 Headway 19
3.1.2 Headway allowance 21
3.1.3 Technical Minimum Running time 21
3.1.4 Running time allowance 22
3.1.5 Dwell time 23
3.1.6 Dwell time allowance 23
3.1.7 Operational processes time 23
3.1.8 Operational processes allowance 24
3.2 Capacity Indicators 24
3.2.1 Number of trains per unit of time 25
3.2.2 Operational stability 28
3.2.3 Running time, stopping time 31
3.3 Intermediate Steps 32
3.3.1 Comfort 34
3.3.2 Expected total trip time 35
3.3.3 Safety, Disruption Management, Human Factors 37
3.3.4 Energy consumption per train, Wear per train 39
3.3.5 Cycle Time 42
3.3.6 Infrastructure usage rate 43
3.4 BuCa Value Indicators 44
3.4.1 BuCa Value Indicators – Society/Economy 46
3.4.2 BuCa Value Indicators – Train Operator / Transport Authority 49
3.4.3 BuCa Value Indicators – Infra Manager 52
3.5 Reflection 54
4 DATO Techniques 56

4.1 ETCS HTD 56
4.2 C-DAS 58
4.3 ATO 59
4.3.1 ATO GoA2 60
4.3.2 ATO GoA4 62
4.4 TMS 63
4.5 NG Brake 65
4.6 DAC for freight rail transport and Full Digital Freight Train 66
4.7 Overview of Interface Matrices and DATO techniques 68
5 Application - Simulation Scenarios 69
5.1 Overview scenarios 69
5.2 Description of geography, traffic, and model parameters (Netherlands) 70
5.2.1 Braking rates 71
5.2.2 Running time allowance 73
5.2.3 Headway allowance 74
5.2.4 Stopping time 74
5.2.5 Timetable and infrastructure variants for HTD and NG Brake 74
5.3 Description of geography, traffic, and model parameters (Sweden) 74
5.3.1 Braking rates 79
5.3.2 Running time allowance 80
5.3.3 Headway allowance 80
5.3.4 Stopping time 80
5.3.5 Additional parameters 80
6 Application - Capacity Indicator results 81
6.1 Capacity indicator results (Netherlands) 81
6.1.1 HTD 81
6.1.2 ATO 85
6.1.3 NG Brake 87
6.2 Capacity indicator results (Sweden) 89
6.2.1 ATO GoA2 89
6.2.2 NG Brake 89
6.3 Energy Efficiency Study Results 90
7 Application – Valuation of Impacts 92
7.1 Parameter inputs 92
7.1.1 The Netherlands 92
7.1.2 Sweden 94

7.2 Valuation of impacts - Results 96
7.2.1 HTD 96
7.2.2 ATO 99
7.2.3 NG Brake 103
7.3 Reflection 107
8 Conclusions 108
References 110
Appendix A: Analytical Study of Energy Efficiency 116
A1 Background and methods 116
A2 Results 119

LIST OF FIGURES

Figure 1: Interface Matrix linking Capacity to Economic and Financial Outcomes 16
Figure 2: Headway for two ETCS L2 trains in the same direction 20
Figure 3: Headway and headway allowances for two ETCS L2 trains in the same direction 21
Figure 4: Speed time diagram (upper panel) and Distance time diagram (lower panel) of technical minimum running time 22
Figure 5: Running time and running time allowance 23
Figure 6: Illustration of UIC406 compressed timetable, Alm to Almo station (NL) 26
Figure 7: Capacity Building Blocks to Number of trains per unit of time 28
Figure 8: Operational stability approximation using punctuality curve 30
Figure 9: Capacity Building Blocks to Operational stability 31
Figure 10: Capacity Building Blocks to Running time and Stopping time 32
Figure 11: Capacity Indicators to Comfort and Travel/Transport demand 34
Figure 12: Capacity Indicators to Expected total trip time 36
Figure 13: Capacity Indicators to Disruption management, Human Factors, and Safety 37
Figure 14: Capacity Indicators to Energy Consumption per train and Wear per train 40
Figure 15: Speed-Distance diagram of different driving strategies 40
Figure 16: Capacity Indicators to Cycle Time 43
Figure 17: Capacity Indicators to Infrastructure usage rate 44
Figure 18: Intermediate steps to BuCa Value Indicators for Society 47
Figure 19: Intermediate steps to BuCa Value Indicators for Train Operator / Transport Authority 50
Figure 20: Intermediate steps to BuCa Value Indicators for the Infrastructure Manager 52
Figure 21: Interface Matrix for ETCS-HTD 57
Figure 22: ETCS Level 2 vs Hybrid Train Detection: effect of shorter virtual blocks 58
Figure 23: Interface Matrix for C-DAS 59
Figure 24: Interface Matrix for ATO GoA2 61
Figure 25: Interface Matrix for ATO GoA4 63
Figure 26: Interface Matrix for TMS 64
Figure 27: Interface Matrix for NG Brake 66
Figure 28: Interface Matrix for DAC and FDFT 67
Figure 29: (E)SAAL corridor (NL) use case map 70
Figure 30: Schematic overview of (E)SAAL Corridor: Stations, tracks, transitions 71
Figure 31: Stockholm Commuter Line (SE) use case map 76
Figure 32: Malmö City Tunnel (SE) use case map 77
Figure 33: Norrköping-Mjölby (SE) use case map 77
Figure 34: Stockholm-Linköping (SE) use case map 78

Figure 35: Schematic overview of UIC406 track segments for SAAL corridor (NL) 81
Figure 36: UIC406 compression for Hvs-Wp, reference L2 model (left) vs minimal axle counter HTD model (right) 83
Figure 37: UIC406 compression for line segment Almo-Alm, comparing old block layout (left) to smaller virtual block layout (right) 83
Figure 38: Delay recovery after deterministic 15min departure delay at Almere Poort with different virtual block lengths 85
Figure 39: Capacity utilization (including headway and running time allowances) - ATO GoA2 and GoA4 relative to manual driver 86
Figure 40: UIC406 compression for line segment Hvs-Wp, comparing human drivers to ATO GoA4 87
Figure 41: 3-minute punctuality for passenger trains in the Netherlands, 2023-2025 94
Figure 42: Semi-quantitative value mapping by effect category and stakeholder (HTD) 99
Figure 43: Semi-quantitative value mapping by effect category and stakeholder (ATO) 102
Figure 44: Semi-quantitative value mapping by effect category and stakeholder (NG Brake) 106
Figure 45: Semi-quantitative value mapping by technique and stakeholder 107
Figure 46: Speed-Distance diagram of different (energy-efficient) driving strategies 116
Figure 47: Reference scenario (IC) effects of the different driving strategies 121
Figure 48: Reference scenario (SPR) effects of the different driving strategies 122
Figure 49: Scenario varying running time allowances (IC) with effects of the different driving strategies 123
Figure 50: Scenario varying running time allowances (IC) Pareto curve 124
Figure 51: Scenario with varying running time allowances (SPR) with effects of the different driving strategies 125
Figure 52: Scenario varying running time allowances (SPR) Pareto curve 126
Figure 53: Scenario with varying performance for acceleration and braking IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 128
Figure 54: Scenario with varying performance for acceleration and braking SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 129
Figure 55: Scenario without varying gradients and with varying speed limits IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 130
Figure 56: Scenario without varying gradients and with varying speed limits SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 131
Figure 57: Scenario with varying gradients and with varying speed limits IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 132
Figure 58: Scenario with varying gradients and with varying speed limits SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right) 133

Figure 59: Sensitivity analysis of varying percentage of trains applying MC and RMS driving strategy and the relative energy savings compared to 100% RMS driving strategy for the IC 134

Figure 60: Sensitivity analysis of varying percentage of trains applying MC and RMS driving strategy and the relative energy savings compared to 100% RMS driving strategy for the SPR 135

LIST OF TABLES

Table 1: Capacity Building Blocks 19

Table 2: Capacity Indicators 25

Table 3: Intermediate steps 33

Table 4: BuCa Value Indicators 46

Table 5: ATO grades of automation 60

Table 6 - Relations between Capacity Building Blocks and DATO concepts 68

Table 7: Simulation models from FP1-WP9 analysed here, by software tool, DATO concepts tested, and traffic type 69

Table 8: SAAL (NL) study parameters for ATO and NG Brake 72

Table 9: Overview of characteristics for Swedish use cases 75

Table 10: Timetable and Simulation parameters for Reference, ATO and NG Brake (Sweden) 79

Table 11: UIC406 compression (%) including Dutch planning allowances for HTD 82

Table 12: Delay recovery after deterministic 15 min departure delay at Almere Poort with different virtual block lengths 84

Table 13: Running time (s/km) and stopping time (s/km) benefits for ATO 86

Table 14: Change in running times (s/km) for NG Brake 88

Table 15: ATO GoA2 results (s/km) for four Swedish lines 89

Table 16: NG Brake results (s/km) for four Swedish lines 90

Table 17: Value of Time for different types of travellers in Sweden 95

Table 18: Economic impacts of HTD, Flevo shorter virtual blocks cases 97

Table 19: Monetized selective economic impacts of HTD 98

Table 20: Overview of BuCa value capacity indicator impacts of HTD scenario 4, illustrative guesses on qualitative effects 99

Table 21: Relative travel time gains (%) of ATO compared to manual driving 100

Table 22: Monetized selective economic and financial impacts for ATO 100

Table 23: Overview of BuCa value indicator impacts of ATO, valued using semi-quantitative value mapping, illustrative guesses on qualitative effects 101

Table 24: Benefits of ATO compared to manual driving 103

Table 25: Relative decrease in travel times (%) for NG Brake scenarios 103

Table 26: Monetized selective economic and financial impacts of NG Brake 104

Table 27: Overview of BuCa value indicator impacts of NG Brake, valued using semi-quantitative value mapping, illustrative guesses on qualitative effects 106

Table 28: Benefits of NG Brake (only dry) compared to manual driving without NG Brake 107

Table 29: Scenarios considered for comparison of the different driving strategies 120
Table 30: Results of the reference scenario IC without varying gradients and speed limits 120
Table 31: Results of the reference scenario SPR without varying gradients and speed limits 121
Table 32: Results of the scenario IC with varying running time allowances 123
Table 33: Results of the reference scenario (SPR) with varying running time allowances 125
Table 34: Results of the scenario IC with varying performance for acceleration and braking for RMS and EETC (RP = reduced performance)..... 127
Table 35: Results of the scenario SPR with varying performance for acceleration and braking... 129
Table 36: Results of the scenario without varying gradients and with varying speed limits IC without varying gradients and speed limits 130
Table 37: Results of the reference scenario SPR without varying gradients and speed limits 131
Table 38: Results of the scenario with varying gradients and with varying speed limits IC without varying gradients and speed limits 132
Table 39: Results of the reference scenario SPR with varying gradients and speed limits 133
Table 40: Results of the sensitivity scenario for manual driving using C-DAS (varying the percentage of MC and RMS application by train drivers) for the IC 134
Table 41: Results of the sensitivity scenario for manual driving using C-DAS (varying the percentage of MC and RMS application by train drivers) 135

2 INTRODUCTION

Many European railway networks face capacity or cost efficiency challenges. We define capacity here in the broadest sense, including effects on punctuality, travel time, safety, infrastructure wear, and energy efficiency. As a result, many European railway networks are interested in ways to improve capacity or cost efficiency. However, the process of building new infrastructure to improve capacity is often lengthy, costly, and constrained by physical, financial and legal obstacles. Similarly, in many cases, any new technology that improves cost efficiency must ideally do so without reducing current performance. In this context, studying the capacity impacts of introducing new technologies on the existing railway network is of high relevance.

The Europe's Rail Joint Undertaking initiated research into constructing a business case for Digital and Automated up to Autonomous Train Operations (DATO). Fundamentally, DATO techniques change the way trains move through the network. Hence, they generate capacity effects. Railway simulations can quantify the size of capacity effects of DATO techniques by modelling the way trains move through the network, comparing scenarios with and without the new DATO technique. One can then consolidate these effects into a business case to evaluate the financial feasibility and the economic potential, or societal value, of a project.

Consequently, the present document constitutes the Deliverable 32.5 "DATO Capacity and Impact Simulations Report", describing part of the fulfilment of Task 32.2 "DATO Operational assessment including HF" and subtask 32.2.1 "Quantifying the operational benefits of ATO". It does so as part of Work Package (WP) 32 "DATO Assessment and Potential identification", which is part of Europe's Rail's Innovation Pillar's Flagship 2 (FP2) "R2DATO".

To quantify the economic and financial impacts of DATO implementation based on railway simulations, we first require a framework that sets up which indicators to measure and how to link them, both on the capacity side and on the economic side.

Indeed, the primary contribution of this document is the construction of a theoretical interface matrix that links traffic behaviour changes with welfare and financial impacts through several layers of categorization, identifying the links between them. Specifically, the interface matrix aggregates *Capacity Building Blocks* into set of four *Capacity Indicators*. The capacity building blocks and indicators together represent the way trains move through the network individually and relative to each other over time and space, from here onwards often referred to as the spatio-temporal behaviour of trains. We then translate these capacity indicators into fourteen *Business Case* (*BuCa) value indicators*, mostly through specified *Intermediate Steps*. In accordance with the strategic review described in Deliverable 32.1 (van den Berg et al., 2026), we group value indicators by the main stakeholder they accrue to.

From the overall interface matrix, we construct variants that represent the effects present for specific DATO techniques, as DATO techniques differ in the way they alter the spatio-temporal behaviour of trains. Specifically, we first explain the technique and then construct interface matrices between traffic behaviour changes and BuCa value indicators for: Automated Train Operation (ATO) Grade of Automation (GoA) 2, ATO GoA4, European Train Control System's Hybrid Train Detection (ETCS-HTD), New Generation Braking (NG Brake), Traffic Management Systems (TMS), and finally Digital Automated Coupling (DAC), potentially as part of the Full Digital Freight Train (FDFT) concept. In such, for an extensive set of DATO techniques, we present models that uniquely identify the potential economic and financial impacts related to the way they alter train traffic behaviour.

A secondary contribution of the document is to apply our interface matrices to process DATO capacity simulation output from a different flagship project in Europe's Rail (FP1-MOTIONAL, WP 8+9). In such, we give an initial idea of the scope and size of capacity effects for some of the DATO techniques simulated there, which are ATO GoA2, ATO GoA4, ETCS-HTD, and NG Brake. Specifically, we calculate a subset of the BuCa value indicator outcomes for five use cases: a dense traffic mainline corridor around Amsterdam (Netherlands), and four corridors ranging from dense commuter to high-speed line type in Sweden. We illustrate the outcomes for the Dutch use case in a semi-quantitative value mapping, in accordance with the overall Business Case methodology put forth in D32.1 (van den Berg et al., 2026).

Results suggest sizeable total benefits from changes in capacity due to ATO, HTD and NG Brake, either through enhanced operational stability or lower travel times. They suggest economic welfare benefits that accrue to society as the largest category. In addition, train operators seem to benefit more from improvements in capacity than infrastructure managers. The results suggest that these DATO techniques have strong potential to enhance the efficiency of the railway system in Europe, encouraging the sector and policymakers to push for further research, development, and implementation projects.

Future research could enhance our application of the interface matrix by applying it within large-scale capacity planning studies that inform real project selection and that can obtain detailed financial data from train operators and infrastructure managers. Additionally, as DATO techniques mature, the matrix can be re-applied to enhanced and higher accuracy capacity simulation studies. Finally, the interface matrix can be applied to any study into changes in the spatio-temporal behaviour of trains even outside the scope of DATO techniques, such as timetable studies, rolling stock acquisition studies, or future railway construction projects.

In sum, this deliverable establishes the link between capacity effects of DATO techniques and economic and financial impacts. We construct a theoretical interface matrix linking the spatio-temporal behaviour of trains, measurable by capacity simulations, with economic and financial value indicators. In addition, we construct DATO-specific versions of this interface matrix. Finally, we apply our model on DATO capacity simulation output from FP1-WP9.

The rest of this deliverable is structured as follows. Chapter 3 presents our interface matrix linking traffic behaviour to economic and financial value indicators. The chapter includes definitions and background explanations for all indicators and their associated links. Chapter 4 explains the studied DATO techniques and presents DATO-technique-specific versions of the interface matrix. Next, Chapter 5 presents the five DATO simulation scenarios from FP1-WP9 we explore in detail, and Chapter 6 presents the results from these simulations in terms of capacity indicators. Consequently, Chapter 7 values the observed impacts in economic and financial terms. Finally, Chapter 8 offers concluding remarks on the document in its entirety.

3 RAILWAY CAPACITY TO BUSINESS CASE – AN INTERFACE MATRIX

Figure 1 below presents the full interface matrix. To our knowledge, this is the first attempt in literature to comprehensively capture economic and financial effects resulting from changes in the spatio-temporal behaviour of trains. The list of variables and the relations we find between them resulted from a two-year-long iterative scoping and refinement process within the group of authors, as well as through peer review rounds and an interface workshop session within the broader work package, as well as external reviews with FP1-WP9, FP2-WP17, and FP2-WP37 within Europe's Rail wave 1, as well as an external review by the long-term capacity management department at ProRail. As a result, we believe it comprehensively captures effects.

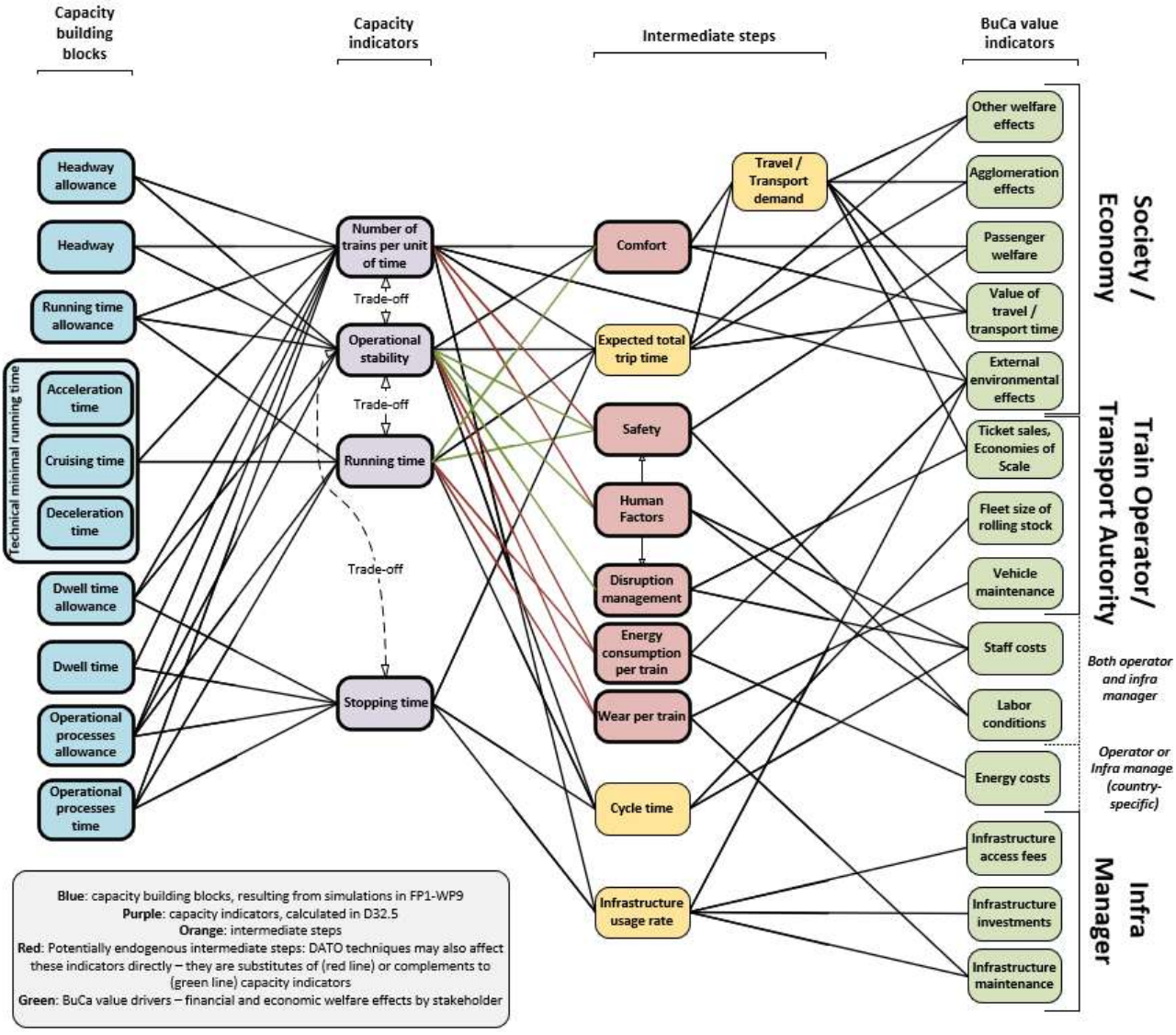


Figure 1: Interface Matrix linking Capacity to Economic and Financial Outcomes

Our interface model follows a three-step approach. First, we categorize the full timetable of a train as a list of *capacity building blocks*, which includes everything from the start-up of trains at the depot or yard up to and including their shutdown at the depot or yard. The sum of these building blocks represents the spatio-temporal behaviour of trains.

Second, we define four *capacity indicators*, which are general constructs that together represent the timetable and performance of a train or line segment. Each is a combination of several capacity building blocks. Microscopic railway simulations usually yield measurements on these capacity indicators (see FP1-D8.3: Pot et al., 2025)

Third, we translate these capacity indicators into *BuCa Value Indicators*, a comprehensive list of economic and financial indicators that (may) change due to changes in railway capacity. Here, we also define *intermediate steps* to clarify the channels through which the relations run, as well as to differentiate effects between the same capacity-to-BuCa-value-indicator pairs that run through different channels.

Before proceeding with individual explanations of the variables and the links between them, we first provide two generic contextual notes to the interface matrix.

1. *Endogeneity*

First, for six variables affected by changes in capacity indicators – comfort, safety, human factors, disruption management, energy consumption and wear – we signal that they may also be affected directly by a DATO technique without being the result of a change in the spatio-temporal behaviour of trains, in addition to there being an effect that does result from a change in the spatio-temporal behaviour of trains.

For example, ATO allows an energy-optimal driving strategy (see Appendix A) and may lower track wear through less wheelslip occurrence (see D32.3 of this WP, Hé et al., 2025). Hence, at the same running time between stations, a train's energy consumption and wear may decrease. This is not a capacity effect, but instead a direct effect of the technique on these indicators.

Hence, for these DATO techniques, the stakeholder collective that decides on railway policy may face a trade-off between potential changes in these variables and potential changes in capacity. In the example, ATO lowering the energy consumption and wear may allow a policymaker to more easily accept faster running times. Hence, changes in these six variables are not just effects from changes in capacity indicators but may also enable or disable them. Thus, in statistical terms, these six variables are endogenous with respect to DATO induced changes in capacity indicators.

Consequently, we give these endogenous intermediate steps a distinctive colour in the interface matrix, with link colours indicating whether sets of indicators are complements (green) or substitutes (red). In the example, a higher running time allows for lower energy consumption per train and wear per train, so running time and energy consumption or wear are substitutes – an increase in one decreases the other. We are attentive to the endogeneity when later discussing the interaction between capacity indicators and these six variables, as well as when generating versions of the interface matrix per specific DATO technique.

2. *Stakeholders*

Second, we group the final *BuCa value indicators* into categories of main stakeholders affected by them. In our interface matrix, we identify three main stakeholders that are usually present in the decision-making process of implementing a large transport project: society, representing a policymaker concerned with maximizing societal welfare, thereby also representing the interests of passengers and industry; the train operator, which can be a freight or passenger operator; and the infrastructure manager.

We base the choice to differentiate effects by stakeholder on the strategic framework within the overall Work Package, described in D32.1 (van den Berg et al., 2026). Their analysis of the sector and of related literature delivered the insight that misalignment between stakeholders is one of the greatest challenges towards successful project implementation. They suggest addressing this challenge by explicitly exploring the stakeholder dimension in the final business case format. The logic is that in an early phase of the project, conflicts may proactively be resolved by better awareness of potential misalignment as well as redistribution of resources among stakeholders.

The rest of this chapter is structured as follows. First, Section 3.1 defines and contextualizes capacity building blocks. Second, Section 3.2 defines capacity indicators, and explains its linkages with the capacity building blocks. Third, Section 3.3 defines intermediate steps, and explains its linkages with capacity indicators. Fourth, Section 3.4 defines the BuCa value indicators, and explains its linkages with capacity indicators through intermediate steps.

3.1 Capacity Building Blocks

This Section explains how to translate railway simulation results within the domain of capacity changes into business impacts. For this, the first step is to qualify how to measure and quantify capacity changes.

Conceptually, railway capacity results from the way trains move across a network. A new policy or technology may alter the way trains move across the network through altering the functioning of signalling systems, traffic control, train characteristics, train schedules, driving behaviour, timetables, and other variables. One can quantify this by measuring the input timetable, executed timetable, train positions and movement variables for each train over time.

Microscopic railway modelling and simulation (Pachl, 2024) is especially suitable to measure the effects of DATO techniques on the spatio-temporal behaviour of trains through a network. It directly models each signal, track, switch, as well as signalling and train protection systems, and then simulates the exact train paths through the network at an accuracy level representative of reality. We refer to D8.3 of FP1-MOTIONAL (Pot et al., 2025), which describes developed models and simulation methods for DATO techniques, for deeper explanation of the appropriateness of microscopic railway modelling and simulation to estimate the effects of DATO techniques.

We conceptualize these measurements into what we call *capacity building blocks*, which represent periods of time that trains spend on a certain type of movement (including stand-still), as well as periods of time between sets of trains. They are minimal technical process times and various margins, which we here define as 'allowance' across all types of processes for clarity purposes. They follow from Andersson et al. (2018) and Hansen & Pachl (2014) and are founded in the International Union of Railways (UIC) Leaflet 451-1 (UIC, 2000).

Table 1 below lists the different categories of capacity building blocks. The following subsections explain them in more detail. The unit of time is in the international standard seconds. In practical reality, you may often see these be converted to hours and/or minutes.

Capacity Building Block	Definition	Unit
Headway	Technical minimum time between two trains where the preceding train does not obstruct the succeeding train	Seconds

	through the signalling system. This is usually measured at the most restrictive block. For single track lines this could also be a train in the opposite direction.	
Headway allowance	Buffer time on the headway to cater for deviations from the planned timetable	Seconds
Technical Minimum Running time	Technical minimum time to move from point A to B	Seconds
-> Cruising time	Time spent driving at a constant speed (e.g., speed-holding)	Seconds
-> Acceleration time	Time spent increasing speed	Seconds
-> Deceleration time	Time spent reducing speed	Seconds
Running time allowance	Supplement time to cater for deviations from the minimum running time	Percentage of technical minimal running time, or distance-based seconds
Dwell time	Stopping time from standstill to setting the train in motion at any stopping points for: boarding and alighting of passengers, loading and unloading of freight, opening and closing of doors, driver and train attendant reaction times	Seconds
Dwell time allowance	Supplement time on the technical minimal dwell time to cater for deviations	Seconds
Operational processes time	Time for other processes that are involved in running a train, including operational processes while standing still mid-journey that are not mentioned under ‘dwell time’	Seconds
Operational processes allowance	Supplement time on the technical minimal operational process times to cater for deviations	Seconds

Table 1: Capacity Building Blocks

3.1.1 Headway

We define headway as the technical minimal time between two trains in the same direction, as constrained by physical reality. Concretely, a train must follow a preceding train by a certain number of seconds that depends on factors like distance, braking performance, signalling, and train characteristics. One can calculate the headway between two trains with blocking time theory.

A block is equivalent to the track between two signals. When a train occupies that block, no other train may use it. This occupation includes the time a train runs between blocking signals, but also the setting and release times of the involved components, as well as the preoccupation time required to maintain safe braking distance to the block entry signal. For an extensive explanation of blocking time theory, we refer to Hansen & Pachl (2014).

When the block occupations of two consecutive trains overlap, there is a conflict that makes the second train face a restrictive signal aspect. In ETCS terms, the train becomes constrained by an

end of movement authority. Hence, it must initiate braking towards the signal marker board that is located at the start of the block the preceding train still occupies. To prevent this in timetable planning, one determines the technical minimum headway as the block where the occupation of the preceding train ends in the same second the block occupation of the subsequent train starts. Hence, at the technical minimum headway, the subsequent train starts to occupy the block immediately after the preceding train releases the block.

Depending on the infrastructure characteristics and timetable pattern, this technical minimum headway can differ across blocks and across different sets of trains. For each specific train pair on a specific line, there will be one block where the technical minimum headway is highest for this train pair on this line. The literature commonly refers to this block as the most restrictive block, the normative block, or the critical block.

Figure 2 below shows a time distance graph of two trains running on the same track, starting and stopping at different platforms for clarity. On the commonly shared track in-between the starting and ending stations, the trains share the same track. There, block occupations of the preceding train restrict the following train from approaching too closely. On the line segment of interest, the technical minimal headway between the trains can be found from the most restrictive block, where block occupations touch.

Note that one may choose to report the resulting headway for further analysis in several ways. One can express it intuitively as the time between the moments the trains pass a certain point related to the most restrictive block, which is usually the start of the block occupation of this block. However, one may also choose to express it as the resulting time between arrival or departure times at nearby train stations, as they are more relevant from the point of view of passenger and freight demand.

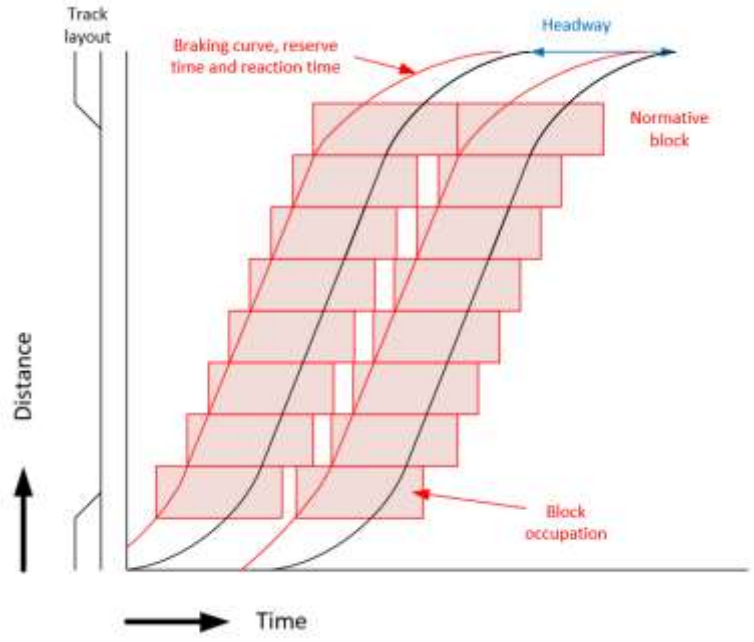


Figure 2: Headway for two ETCS L2 trains in the same direction

3.1.2 Headway allowance

Trains will have a deviation in running times and departure times due to real operational and engineering conditions. Therefore, timetable designers may add extra time between two trains to prevent conflicts. This is the headway allowance, colloquially often referred to as headway buffer. The total of the headway and buffer on the most restrictive block gives a minimal planned headway, as shown in Figure 3 below.

Much like the running time allowance, the headway allowance norms differ between countries and logistical contexts. In the Netherlands, the basic hourly timetable uses a buffer of 60 seconds for passenger trains and 0 seconds for freight trains. Freight trains take their buffer from being timetabled too often and with an overestimated weight, length and underestimated braking performance relative to their averages. In Sweden, there are guidelines of the minimum headway ranging from 2 minutes to 6 minutes depending on the length and type of route. In Spain, there is no defined headway allowance, and the headway between trains depends on the traffic management system planning rules and the length of the block.

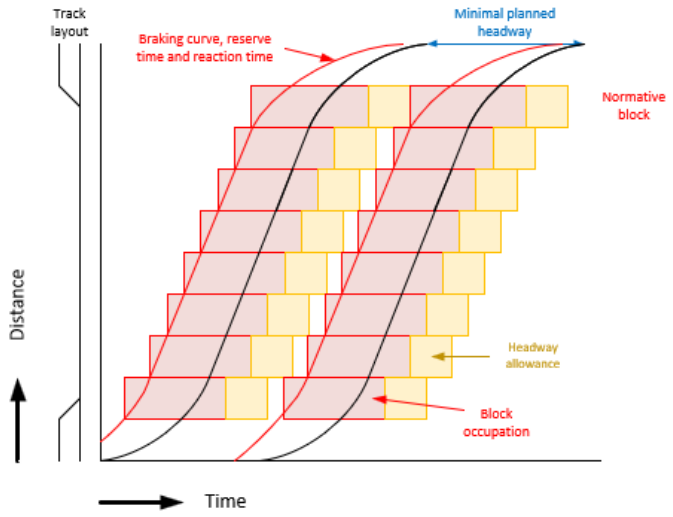


Figure 3: Headway and headway allowances for two ETCS L2 trains in the same direction

3.1.3 Technical Minimum Running time

The technical minimum running time represents the time taken while moving between two different physical locations, usually between scheduled station stops. In other words, the technical minimum running time captures the lowest possible amount of time that a train can take to travel between start and destination. To achieve this lowest possible travel time, a train would accelerate as quickly as possible up to maximum speeds, cruise at the maximum speeds for as long as possible, then decelerate as quickly as possible towards lower maximum speeds as well as to the final stop. We can divide these phases of the movement of a train into (technical minimum) acceleration time, cruising time and braking time. Figure 4 below sketches a speed-time and distance-time diagram of a train as it runs through some different phases.

If the train does not run as fast as possible, it can employ a coasting strategy to replace some of the engaged braking phase. Coasting means that the traction control is in a neutral position. Here, the train slowly decelerates through friction, without applying any braking force. In traditional capacity

literature, the phases of acceleration, cruising, coasting and deceleration are often mentioned (e.g. Hansen & Pachl, 2014), but their relationship with minimising the running time is not homogeneous in size and sign. For example, a train that does not accelerate to the maximum line speed would have a lower acceleration time but take longer to reach its next stop in totality. Hence, within our methodology of defining capacity building blocks, we aggregate the movement phase of the train into the single building block of technical minimum running time.

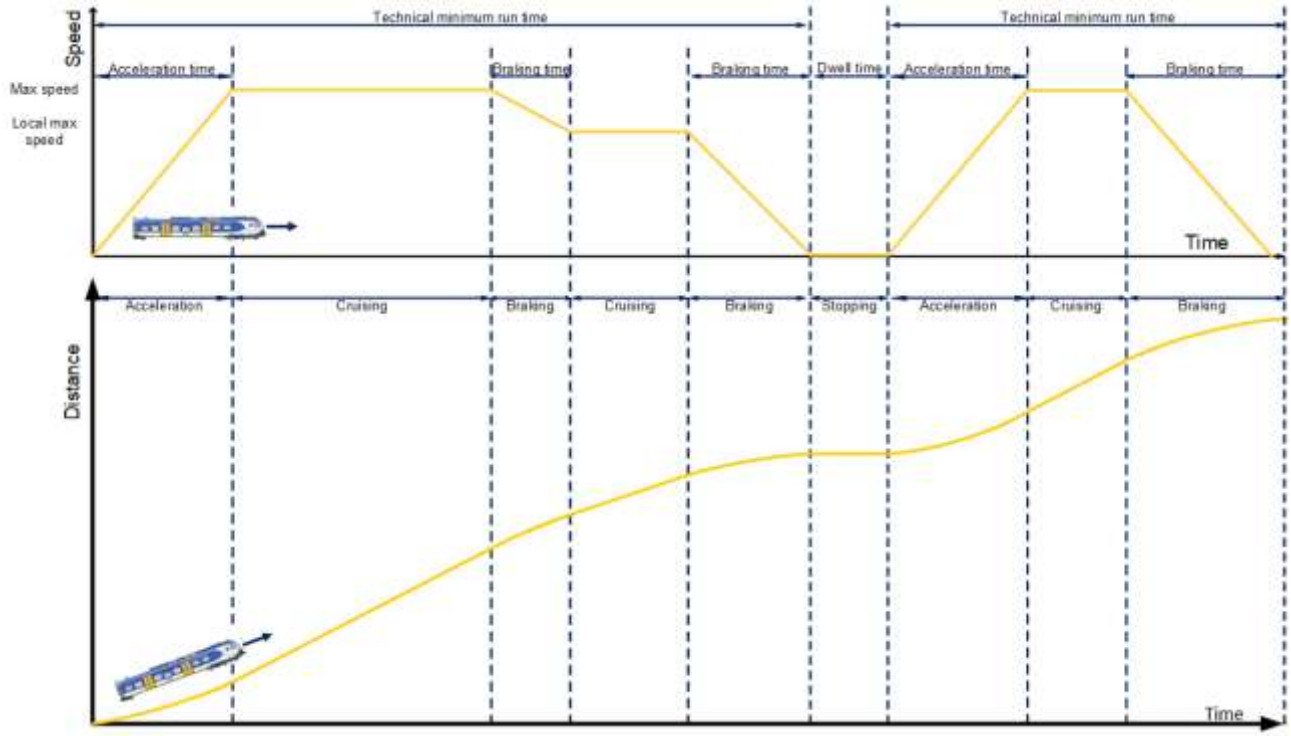


Figure 4: Speed time diagram (upper panel) and Distance time diagram (lower panel) of technical minimum running time

3.1.4 Running time allowance

The running time allowance, colloquially often referred to as running time supplement or slack, represents the time that may be added on top of the technical minimal running time within a timetable. It accounts for deviations from perfect operational conditions that would otherwise lead to timetable delays. More specifically, it consists of driver variability and engineering variability – the former for differences in driving inputs given, and the latter for infrastructure conditions like weather, temporary speed restrictions, and small delays. Usually, timetable planners set the running time allowance as a percentage of the technical minimal running time. Some countries may add rules for a specified number of seconds per unit of distance.

It is important to note that the running time allowance is a timetable construct. Trains in real life operation are not constrained in their acceleration, max speed and braking performance by some percentage points in the way they may be in the timetable planning. Hence, in real life operation, trains that drive on time can use the running time allowance in their timetable for energy-efficient driving with coasting. Also, trains that are delayed can use the running time allowance to catch up again.

The running time allowance percentage may differ across countries and traffic types. For example, the Netherlands use a running time allowance of 7 percent for mainline passenger traffic, 6 percent for mainline passenger traffic where drivers instead of conductor lead the departure process, 4 percent for rural passenger traffic, and 0 percent for freight traffic. In Sweden, the running time allowance consists of a 3% allowance to cover driver variation and a distance-based allowance depending on train type and single-track/double-track (2-4 minutes per 100 km).

In addition, the distribution of the running time allowance across the different movement phases (acceleration, cruising, braking) differs across countries. For example, the Netherlands and Sweden distribute the allowance evenly to all the phases, exemplified in Figure 5 below, whereas Germany solely distributes the running time allowance at the cruising phase. In Spain, the allowance may be distributed evenly across all phases or concentrated at solely the braking phase.

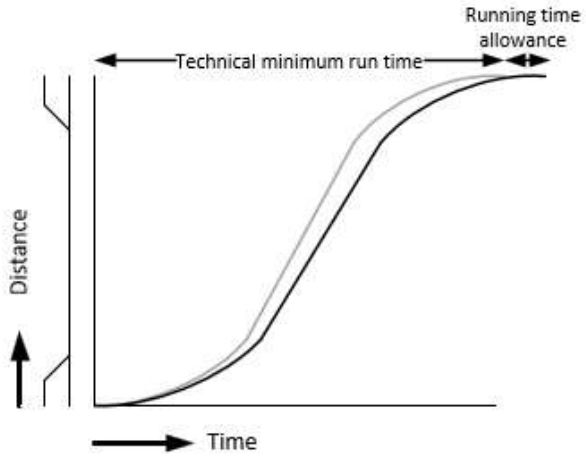


Figure 5: Running time and running time allowance

3.1.5 Dwell time

Dwell time is the stopping time from standstill to setting the train in motion at any stopping points, spent exclusively on the following three processes: (1) boarding and alighting of passengers or unloading and loading of freight, (2) opening and closing of doors, and (3) departure processes by the train attendant and driver, including their response times.

3.1.6 Dwell time allowance

One may define a dwell time allowance, usually defined in seconds, to cater for variations in boarding and alighting or loading and unloading processes without causing timetable conflicts. In such, it caters for time deviations in the dwell processes. In addition, a railway timetable planner may add some allowance time on top of the technical minimum dwell time due to timetable restrictions, such as waiting to be overtaken, waiting for a crossing train from the other direction, awaiting a connecting train, adhering to a cyclical timetable, or preventing some other scheduled conflict.

3.1.7 Operational processes time

Operational processes are a blanket category of operational processes not captured by the other capacity building blocks. They may take place during a journey as well as before and after a journey. The times these processes take consume capacity. These times can differ from half a minute (e.g.,

train startup time), one to two minutes (e.g., the driver walks to opposite cabin for direction change) to several hours (e.g., shunting of freight trains at the yard). We do not present an exhaustive list of operational processes here, as this is outside the scope of this report. For example, Deliverable 32.4 (Lo et al., 2026) devotes a significant part of the full report to a discussion of changes in human operational processes due to ATO GoA2 implementation. Instead, where applicable, we mention the specific operational process time category that changes because of DATO implementation where relevant in subsequent chapters.

3.1.8 Operational processes allowance

Operational processes have technical minimal times, but a timetable planner may add allowance time to cater for deviations. For example, weather conditions may extend the time certain processes take. The allowance can be a few seconds for a simple action or a few hours for loading/unloading of freight trains.

3.2 CAPACITY INDICATORS

From combinations of the capacity building blocks, we define *capacity indicators*: four general constructs that represent the timetable and performance of a train or line segment. Table 2 below lists these four indicators, as well as a short description of their definition and suggested units of measurement.

Capacity Indicator	Definition	Unit
Number of trains per unit of time	Measure for the infrastructure / track occupation, framed in a unit applicable to economic and financial outcomes	UIC406 capacity utilization including headway allowance time (or some other method of timetable compression), then calculate how many trains can be added
Operational stability	The ability of a set of trains to adhere to their scheduled train paths, absorb delays, and withstand timetable design errors and suboptimal operational conditions.	We propose two units: (1) Seconds (recovery time at delay point or until the first fully punctual train; total delay accumulated by all trains at all stops); number of trains affected. Only truly represent effect within model scope when using stochastic simulation. (2) If no valid stochastic delay data is available, one may also use UIC406 capacity utilization, an empirical punctuality curve, and an assumption on rate of hindrances, to determine the expected average decrease in delay minutes corresponding to a decrease in planned capacity utilization. Can be

		qualitatively supported by deterministic simulations of (1). Note the analysed timetable must be feasible, i.e. not contain (many or large) scheduled conflicts.
Running time	Set of all running times between stations, for all train patterns	Seconds
Stopping time	Set of times spent standing still at stations, for all train patterns. This also includes stopping time before its departure from the starting yard / after its arrival to the final yard	Seconds

Table 2: Capacity Indicators

The first two categories build heavily on the seminal work by Goverde & Hansen (2013), who posit five timetable performance indicators:

1. Infrastructure or track occupation, measuring how much infrastructure capacity a timetable pattern's block occupations utilize.
2. Timetable feasibility, measuring the ability of trains to adhere to their scheduled train paths, with a norm of zero scheduled conflicts.
3. Timetable stability, the ability of a timetable to absorb delays such that delayed trains return to their scheduled train paths.
4. Timetable robustness, the ability of a timetable to withstand design errors, parameter variations, and changing operational conditions.
5. Timetable resilience, the flexibility of a timetable to prevent or reduce secondary delays using dispatching.

Our capacity indicators map to these as follows. The *number of trains per unit of time* reflects (1), while *operational stability* reflects (2-5). Our final three capacity indicators are *running time*, *stopping time during the journey*, and *stopping time before/after the journey*. As they make up stages of train operation that cost time and space, they have economic and financial consequences. Hence, we include them as indicators of capacity. The subsequent subsections explain the capacity indicators in more detail, including an explanation of the links with capacity building blocks for each capacity indicator.

3.2.1 Number of trains per unit of time

3.2.1.1 Definition

A railway system may generate more economic welfare or become more cost effective when more trains are using the same infrastructure, as it can accommodate more travellers and freight for largely the same infrastructure costs. A technology or policy that increases the potential number of trains per unit of time that a track can handle may therefore be strongly beneficial in certain market conditions. Such conditions could be the line already being at full capacity while there is still potential transport demand, either directly or indirectly through the attractiveness of higher service frequency.

The *number of trains per unit of time* reflects Goverde-Hansen timetable performance indicator (1). They suggest measuring it as capacity utilization after timetable compression, for which UIC leaflet 406 (UIC, 2013) describes a widely acknowledged method. Specifically, UIC406 compression puts all planned train paths – without headway allowances – as close together as possible while keeping the scheduled order of trains the same. One can express the resulting time consumed to run this compressed timetable as some percentage of a time window in which all scheduled trains should fit.

Figure 6 below shows an example of a UIC406 compressed timetable, including the block occupations of the scheduled trains. Yellow and red arrows indicate the normative blocks, where block occupations by subsequent trains border each other exactly. In the example, the analysed time window is one hour. The first scheduled train in this hour is *SLT 5300-11*. After all scheduled trains are subsequently aligned below, the compression algorithm then prescribes to repeat the pattern by scheduling a new virtual version of train *SLT 5300-11* immediately below the final train within the original scheduled hour. The second within the hour in which this new train's first block occupation appears is the first time a new train path can theoretically be added. This second expressed as percentage of the hour is the UIC406 compression percentage. In the Figure 6 example, this is at second 1734, at 9:28:53 in the hour, corresponding to a UIC406 compression percentage of $\frac{1734\ s}{3600\ s} * 100\% = 48.17\%$.

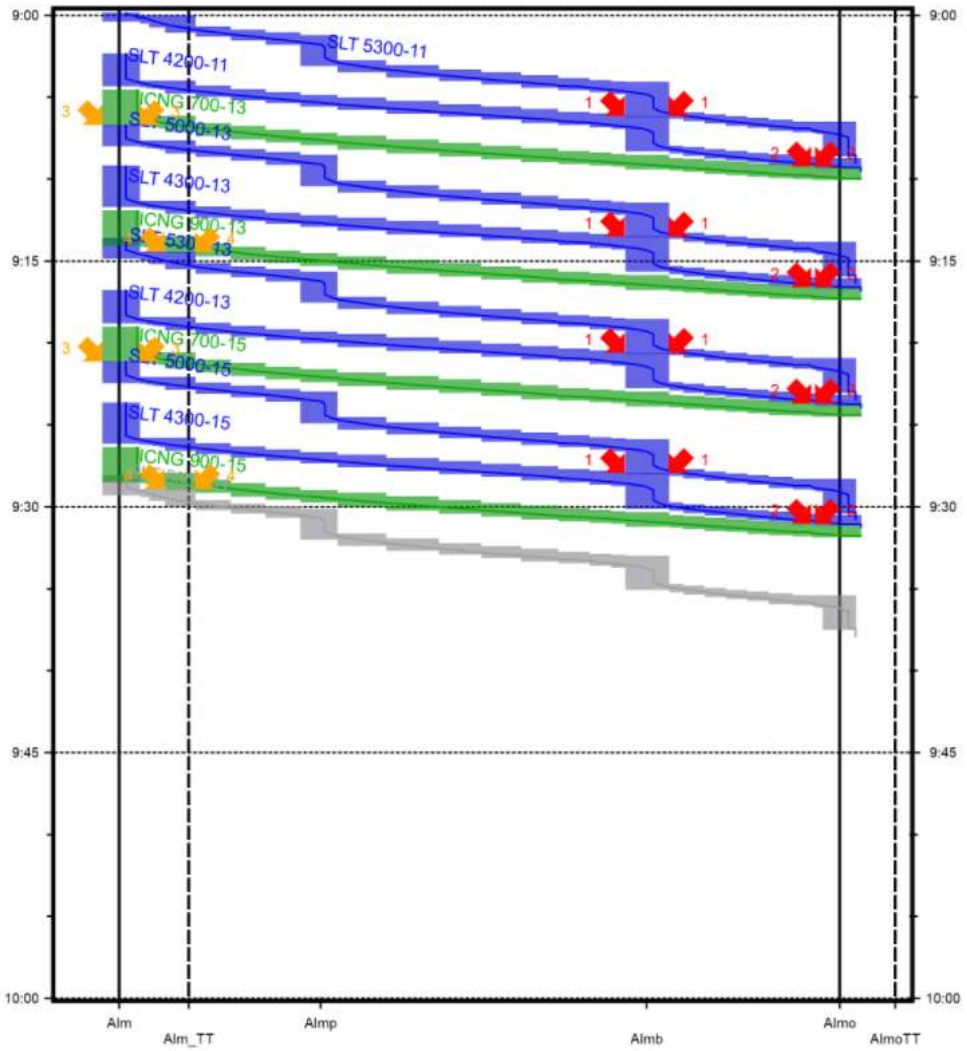


Figure 6: Illustration of UIC406 compressed timetable, Alm to Almo station (NL)

The percentage represents the minimum possible time needed to run trains on the selected infrastructure. One important difference of philosophy we propose when compared to the UIC406 leaflet is how to draw further conclusions from this percentage measurement when assuming realistic instead of technical minimum planned headways and running times.

Specifically, the UIC406 leaflet suggests blanket maximal values depending on traffic type (from 60 to 85%) (UIC, 2013) to realistically run a stable timetable. However, in case one has defined headway allowances and measured the train paths as including the defined running time allowance, then one can endogenize the assumption on running a stable timetable into the calculated value. Specifically, one can simply add the defined headway allowance, expressed as percentage of time within the analysed time window, to the measured UIC406 percentage from train paths that include the running time allowance. The resulting total percentage should then simply be at most equal to 100% to have a stable timetable, no matter the traffic type.

From this resulting realistic capacity utilization percentage, one can deduce how much of the existing track capacity per unit of time is utilized by existing train paths in realistic conditions, as well as how many new trains can potentially be added while maintaining timetable stability.

In the example of Figure 6, each train path is measured as the sum of the technical minimal running time and the running time allowance defined for timetable stability. Blue short-distance trains have a headway allowance of 45 seconds, and green long-distance trains have a headway allowance of 60 seconds. Within the time window of one hour, this corresponds to an additional occupied timetable percentage of $\frac{8*45s+4*60\,s}{3600\,s} * 100\% = 16.67\%$. The resulting total capacity utilization is 64.84%. As a result, there is still 35.17% of an hour remaining to plan new trains in the example.

Note that the UIC406 leaflet methodology of timetable compression has certain downsides. For example, it has trouble considering broader network effects. Namely, it is limited to tracks where there is no intermediate entry of new trains that would complicate the order of trains after compression. One should take this into account when analysing results, where qualitative knowledge of the studied timetable and infrastructure should guide logical line segments of analysis, and proper disclaimers with their associated number outcomes.

3.2.1.2 Links with Capacity Building Blocks

The number of trains per unit of time relates to all capacity building blocks. Figure 7 below shows these relations, including units of measurement. Concretely, first, operational process time, dwell time and its allowances determine how quickly a train vacates blocks that it stands still in. A larger dwell time allows less trains per unit of time, since individual trains will occupy the tracks of their scheduled stops for longer. A larger dwell time allowance compounds this effect. Similarly, a higher operational process time allows less trains per unit of time, since individual trains will occupy the track they are performing their operational process at for longer. A higher operational processes allowance compounds this effect.

Second, technical minimal running time and its allowance determine how quickly a train runs through blocks. Generally, a longer technical minimal runtime allows less trains per unit of time since trains will take more time to finish their routes. Also, a higher running time allowance allows less trains per unit of time since individual trains will occupy the timetabled tracks they are running on for longer. One nuance exists, that becomes relevant in mathematical edge cases. A railway system has the highest number of trains per unit of time if the train traffic is homogenous, the trains run with the same speed and have the same stopping pattern. The best example of this is a metro system. Thus,

when there is a large average speed difference between trains, and only the technical minimal running time of the faster train improves, the increase in average speed difference may sometimes negatively affect the number of trains per unit of time.

Finally, headway and its allowance determine the space between the resulting block occupations. A larger headway allows less trains per unit of time, since individual trains will occupy more time in a planned timetable. A larger headway allowance compounds this effect. Conversely, a smaller headway and headway allowance will give more room for other trains to fit in the timetable.

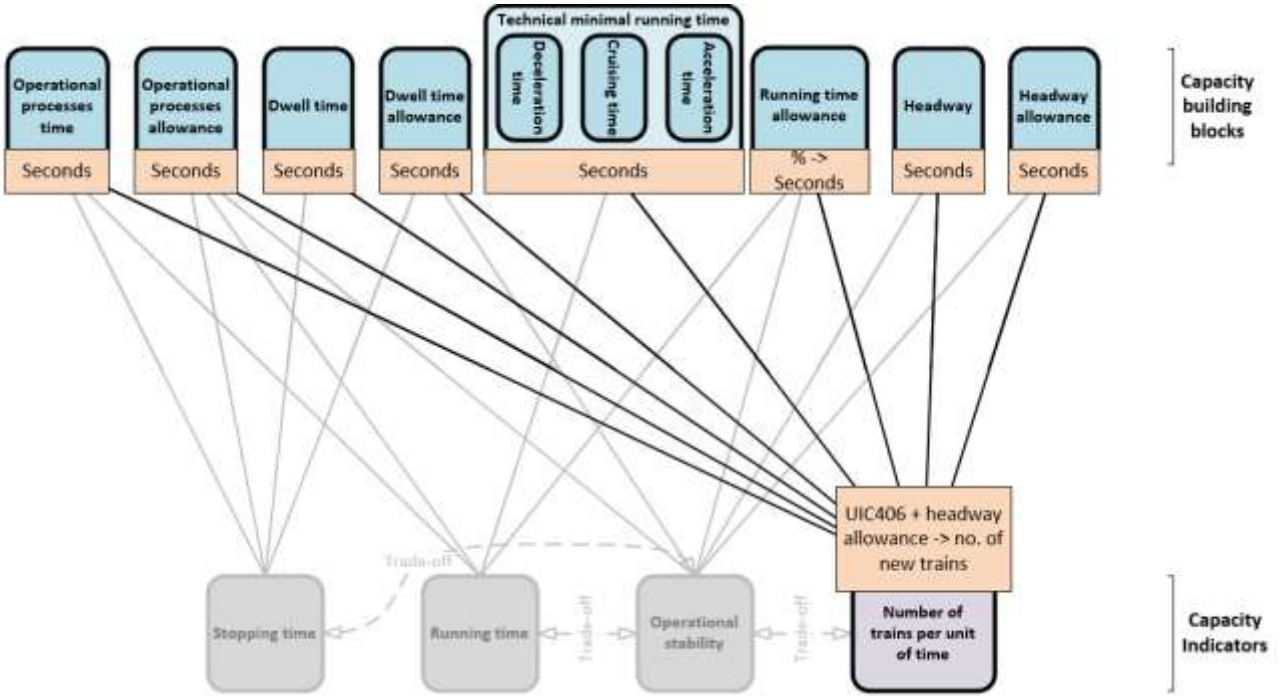


Figure 7: Capacity Building Blocks to Number of trains per unit of time

In conclusion, all capacity building blocks together determine the remaining timetable space to potentially add more trains. One can intuitively measure the remaining space through UIC406 timetable compression including running time and headway allowances. This shows the potential to stably add an extra train or extra scheduled stop to the timetable pattern.

Note that the capacity indicator *Number of trains per unit of time* negatively relates to allowance times, while *Operational Stability* positively relates to allowance times. Consequently, there exists a trade-off between Operational Stability on the one hand, and Number of trains per unit of time on the other hand.

3.2.2 Operational stability

3.2.2.1 Definition

A traveller or transportation company wants to have certainty about the departure and arrival time or punctuality of the train, as well as limit their delay time when one does occur. In other words, delays are measured in time units either for individual trains or aggregated on some level, while punctuality

is the share of trains being delayed beyond some defined threshold number of seconds. We define operational stability as a combination of both.

Timetable designers achieve operational stability by adding allowances in the scheduled timetable, as the previous section *Capacity building blocks* outlines. In general, a larger allowance will lead to a higher operational stability but will enlarge travel and transportation times. The margins can be decreased if the variance in realised running times decreases while keeping operational stability at an equal level, or when different choices are made regarding the optimal operational stability level.

Operational stability represents timetable performance indicators (2-5) as defined by Goverde & Hansen (2013). One ensures timetable feasibility (2) through scheduling a conflict-free timetable, and we follow Goverde & Hansen (2013) by framing this as a requirement for stable railway operation – in other words, a requirement that all scenarios in a comparative study should aim to fulfil.

One may measure timetable stability (3) by inputting delays and then measuring recovery time, number of affected trains, and/or total accumulated delay. To get a representative picture of the real economic and operational consequences of delays, the input delays must be representative of reality. This requires stochastic simulation with realistic delay probability distributions.

However, it may not be feasible to acquire accurate delay probability and delay size distribution data from real life, especially in case of new DATO techniques (see FP1-D8.3; Pot et al., 2025). In this case, we suggest that one can alternatively measure changes in operational stability through changes in the UIC406 compression percentage.

Concretely, one can express changes in the UIC406 compression percentage as an average value of free unoccupied seconds per train before a subsequent train gets delayed. One also requires an assumption on the rate of restrictive movement authorities or signal aspects per unit of distance. Given these, one can shift the empirical punctuality curve from the contemporary situation to express the operational stability benefit.

Figure 8 below demonstrates this. A fictive example of a punctuality curve shifts horizontally by an example value of 15 seconds as response to some DATO technique. Intuitively, with the assumption of exactly one instance of running into an unplanned restricted movement authority per average section of a train run, the timetable compression yielded a value that makes trains have 15 seconds more unoccupied block space behind them at the planned critical block. Hence, subsequent trains will now be delayed only if the preceding train was 15 seconds more delayed than in the reference scenario. As a result, all passengers that experienced 15 seconds or more delay during their trip will now see a reduction of the full 15 seconds of the potential delay reduction, if we assume that each passenger would on average encounter one restrictive signal aspect per trip. In addition to this, some passengers previously experienced less than 15 seconds of delay. For this group, the reduction in delay time is half when assuming a locally linear original punctuality curve, which is a good approximation for small changes in delays.

The method has several intrinsic biases. Namely, the method eliminates the influence of timetable and infrastructure heterogeneities like a variable train order, infrastructure bottlenecks in delayed situations, and additional unrequired allowance time that may have been present in the timetables that yielded the empirical punctuality curve. Nonetheless, in absence of valid stochastic delay data, it represents a good fall-back option for ballpark effect estimates. To confirm that these biases are not prohibitive, one may support such an analysis of operational stability with simulations that impose deterministic delays. This means one simulates cases where a predefined delay is imposed on some

(set of) train(s) and then measures the same delay indicators as for the stochastic tests, which are recovery time, total delay, and number of trains affected.

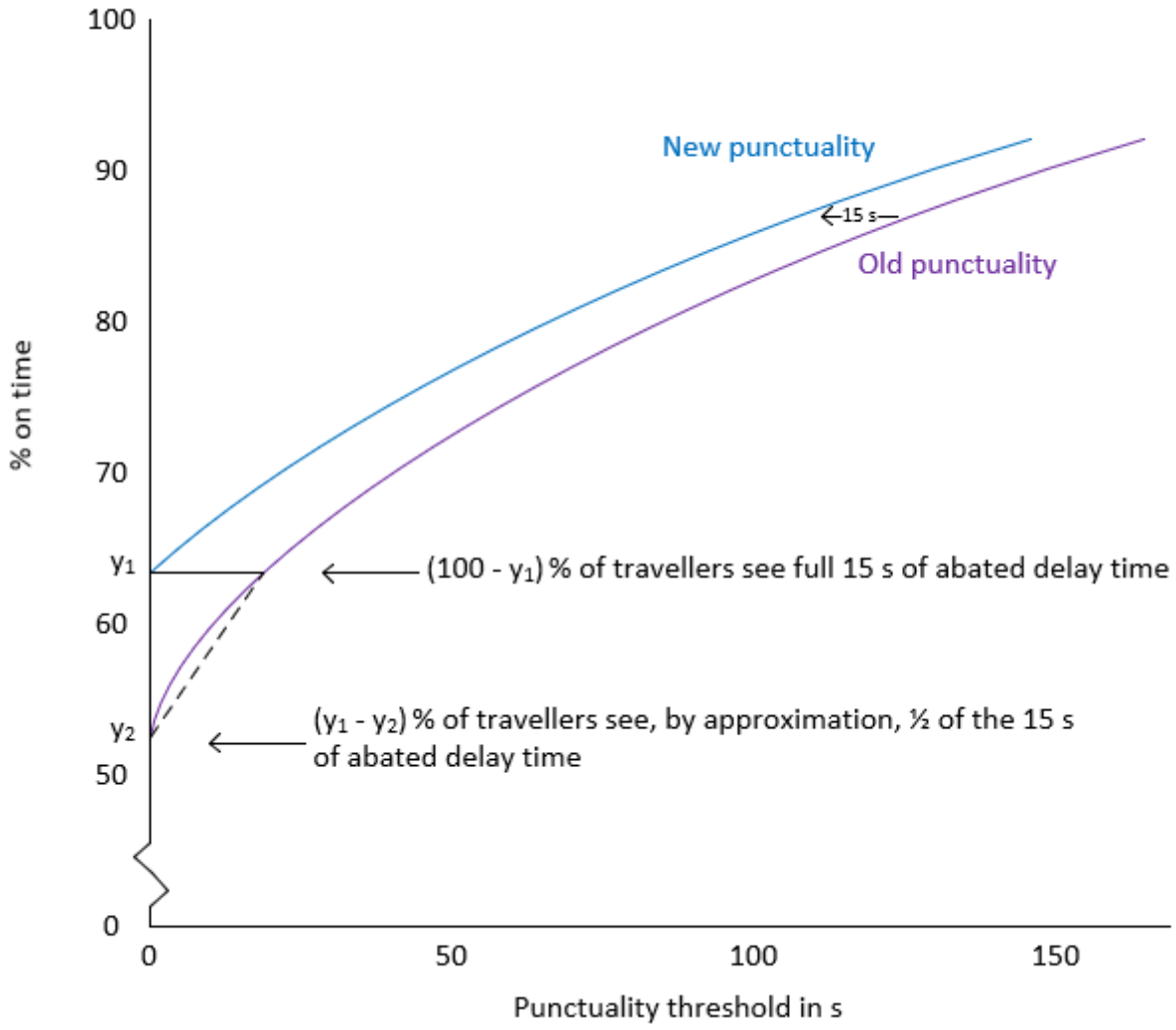


Figure 8: Operational stability approximation using punctuality curve

To cover timetable robustness (4) as defined by Goverde & Hansen (2013), one may ideally aim to keep this value stable between null and alternative scenarios through assumptions on changes in headway allowance, running time allowance, dwell time allowance and operational processes allowance parameters across scenarios, with the target of reaching the same level of robustness. Finally, one may measure timetable resilience (5) as delay recovery when keeping the same set of dispatching decisions across scenarios, or by implementing different dispatching decisions across scenarios if a new technique or policy would lead to such.

In sum, we suggest measuring operational stability through measures of delay recovery time, total accumulated delay, and number of trains affected. One can use delay distributions to transform these into total delay time, delay recovery time and number of trains affected per unit of time. In case reliable running time and delay distributions are not available, which is currently the case for DATO techniques in most European countries, a deterministic simulation is an acceptable alternative to measure operational stability effects.

3.2.2.2 Links with Capacity Building Blocks

Figure 9 below shows the relations between capacity building blocks and operational stability. We establish five links between them. These are the four allowance times, as well as headway.

In general, larger allowances improve operational stability. Namely, a larger allowance covers larger deviations or delays in the related process times without causing a timetable conflict. In addition, if the headway decreases through shorter blocks, braking distances or signalling process times with the same number of trains, this will lead to a higher operational stability since there are less conflicts and recovery times are shorter.

Note that the capacity indicators number of trains per unit of time, running time and stopping time negatively relate to allowance times, while operational stability positively relates to allowance times. Consequently, there exists a trade-off between operational stability on the one hand, and number of trains per unit of time and running time on the other hand.

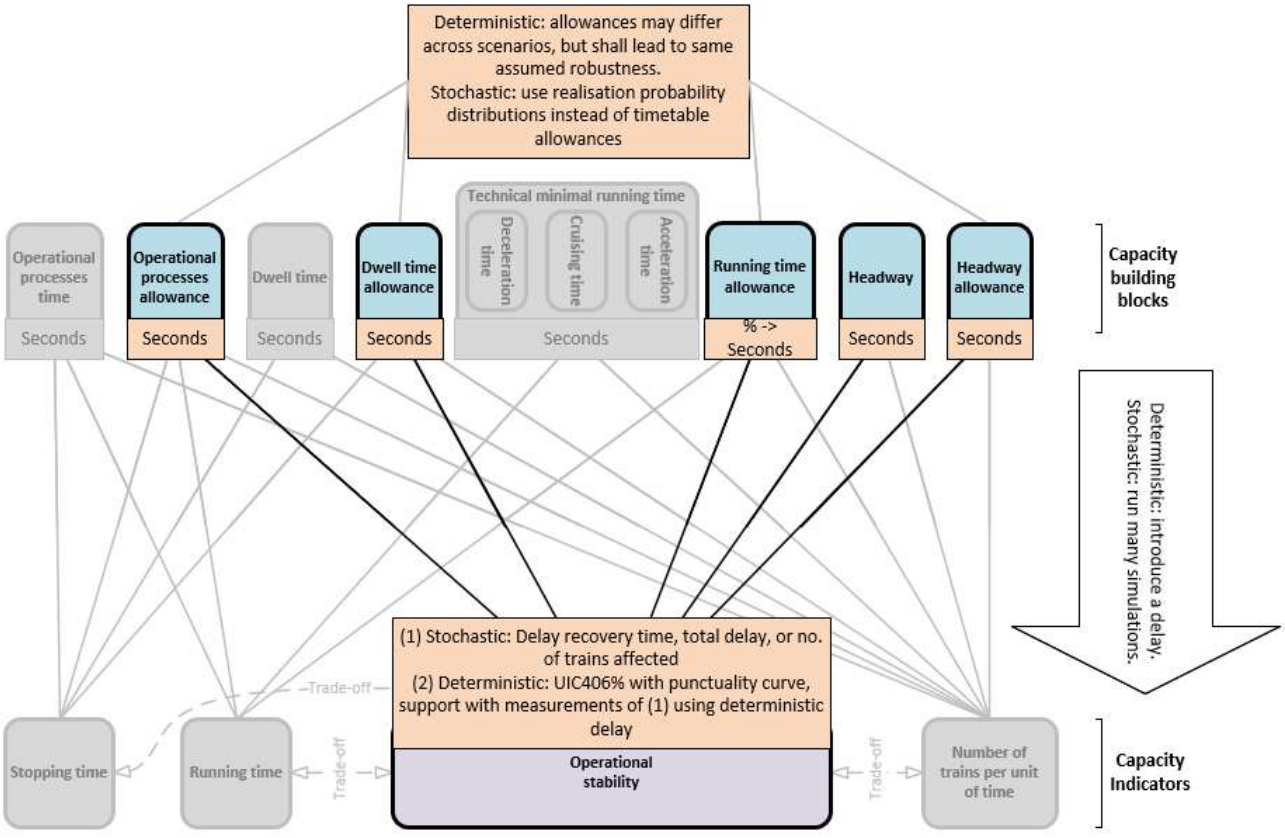


Figure 9: Capacity Building Blocks to Operational stability

3.2.3 Running time, stopping time

The other two capacity indicators we identify are running time and stopping time. We mainly opt for this division because of differential effects of different techniques on these different stages of train operation time.

Running time represents the time a train takes while moving between adjacent scheduled stops. By contrast, stopping time represents the time that a train has a scheduled stop. This can be at station

stops, but also at other scheduled stops, such as at sidings to let other trains pass ahead. Stopping time can also represent the time that a train stands still while preparing for its journey and after it finishes its journey. More concretely, the stopping time also includes the time during which the train is standing still in the yard, with the restriction that at least one staff member or software algorithm is carrying out some task related to preparing the train before its journey or shutting down the train after its journey.

One can measure running time and stopping time straightforwardly in seconds. Their relations to the relevant capacity building blocks – Operational processes time and allowance, Dwell time and allowance, and Technical minimal running time and allowance – are also straightforward. Figure 10 below presents these links and the associated units of measurement.

Note that the capacity indicators running time and stopping time negatively relate to allowance times, while operational stability positively relate to allowance times. Consequently, there exists a trade-off between running / stopping time and operational stability.

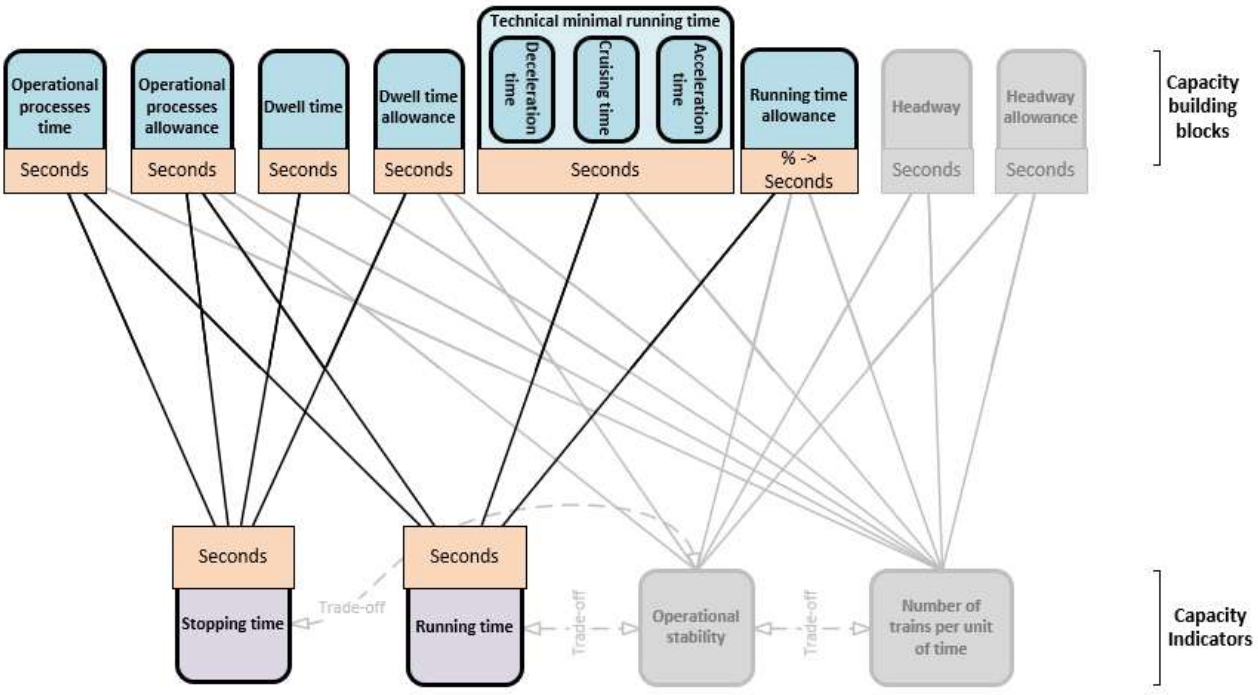


Figure 10: Capacity Building Blocks to Running time and Stopping time

3.3 INTERMEDIATE STEPS

We define intermediate steps between the capacity indicators on the one hand and BuCa value indicators, which are social/economic and financial indicators, on the other hand. Table 3 below summarizes the intermediate steps. These intermediate steps serve three purposes. First, they separate different effects that run between the same capacity indicator to BuCa value indicator pairs, which may have separate associated parameters for economic quantification. Second, they clarify the logic behind the interfaces between capacity indicators and BuCa value indicators. Third, they highlight the six statistically endogenous variables that we argue are either substitutes or complements to changes in capacity indicators for at least one DATO technique. We explain the

rationale behind the potential endogeneity for these variables in the section below. Note that other intermediate steps may also be endogenous when applying the interface model to another technology or policy intervention.

Intermediate step	Definition	Unit
Comfort	Indicator for the level of comfort experienced during a trip, spanning constructs like crowding, platform waiting time, and ride quality. Endogenous for at least one DATO technique.	As multiplier on Value of travel time or qualitative. It also imposes a constraint on max braking rate.
Expected total trip time	The expected time taken by all passengers and freight units when travelling from their origin to their destination, including time spent off the train.	Seconds
-> Travel / Transport demand	Travel (passenger) or transport (freight) demand follows from the expected total trip time and the comfort level of the trip.	Number of passengers or freight units per unit of time
Safety	Risk of accidents. Endogenous for at least one DATO technique.	Qualitative or as number of accidents (or monetized value of accidents) per passenger-km, ton-km or staff-km
Human Factors	Catch-all term for operational behaviour by drivers, operators and staff involved in the operation of a train. Itself influences *safety* and *disruption management*. Endogenous for at least one DATO technique.	Qualitative, may be constraint on available capacity benefits through constrained usage of technology (see D32.4; Lo et al., 2026)
Disruption management	Sum of costs for activities undertaken to mitigate the negative effects if/when trains get delayed or cancelled. Endogenous for at least one DATO technique.	Euros per passenger-km or ton-km
Energy consumption per train	Energy consumption per train. Endogenous for at least one DATO technique.	kWh per passenger-km or ton-km
Wear per train	Degradation of the rails, as well as of the wheels of the train. Endogenous for at least one DATO technique.	Wear damage indices per train movement (see D32.3; Hé et al., 2025)
Cycle time	Trainset cycle time: the minimal time it takes to cycle one trainset from the start of their first journey to the start of their next journey, including turnaround allowance time.	Seconds. Note that timetables that require cyclical hours sometimes impose an up- and downwards restriction on cycle time.
Infrastructure usage rate	Frequency and severity of usage of the track.	No. of trains (per type), weight in ton-km, or number of axles passed; all per unit of time

Table 3: Intermediate steps

3.3.1 Comfort

Comfortable travel has many attributes that influence the generalized cost of travel. First, passengers prefer to minimize waiting times at platforms (Wardman, 2004; Small & Verhoef, 2007). Second, the ability to obtain a seat on a train strongly enhances on-board productivity and travel experience (Wardman & Whelan, 2011; Warffemius et al., 2016). The available space and seat quality enhance this effect (Warffemius et al., 2016). Third, a smooth ride quality is preferable. Finally, high service frequency reduces expected waiting time and allows passengers to adopt “turn-up-and-go” travel behaviour (Mohring, 1972; Small & Verhoef, 2007).

As such, the comfort level determines the extent to which passengers can use their travel time productively or pleasantly, thereby affecting the value of travel time (Kouwenhoven & de Jong, 2018; Kroes & Koopmans, 2014) as well as the disutility suffered during delays (van Hagen & de Bruyn, 2015).

We propose that comfort relates to three capacity indicators. These are the number of trains per unit of time, operational stability, and running time. Figure 11 below highlights these relations, as well as potential units of measurement.

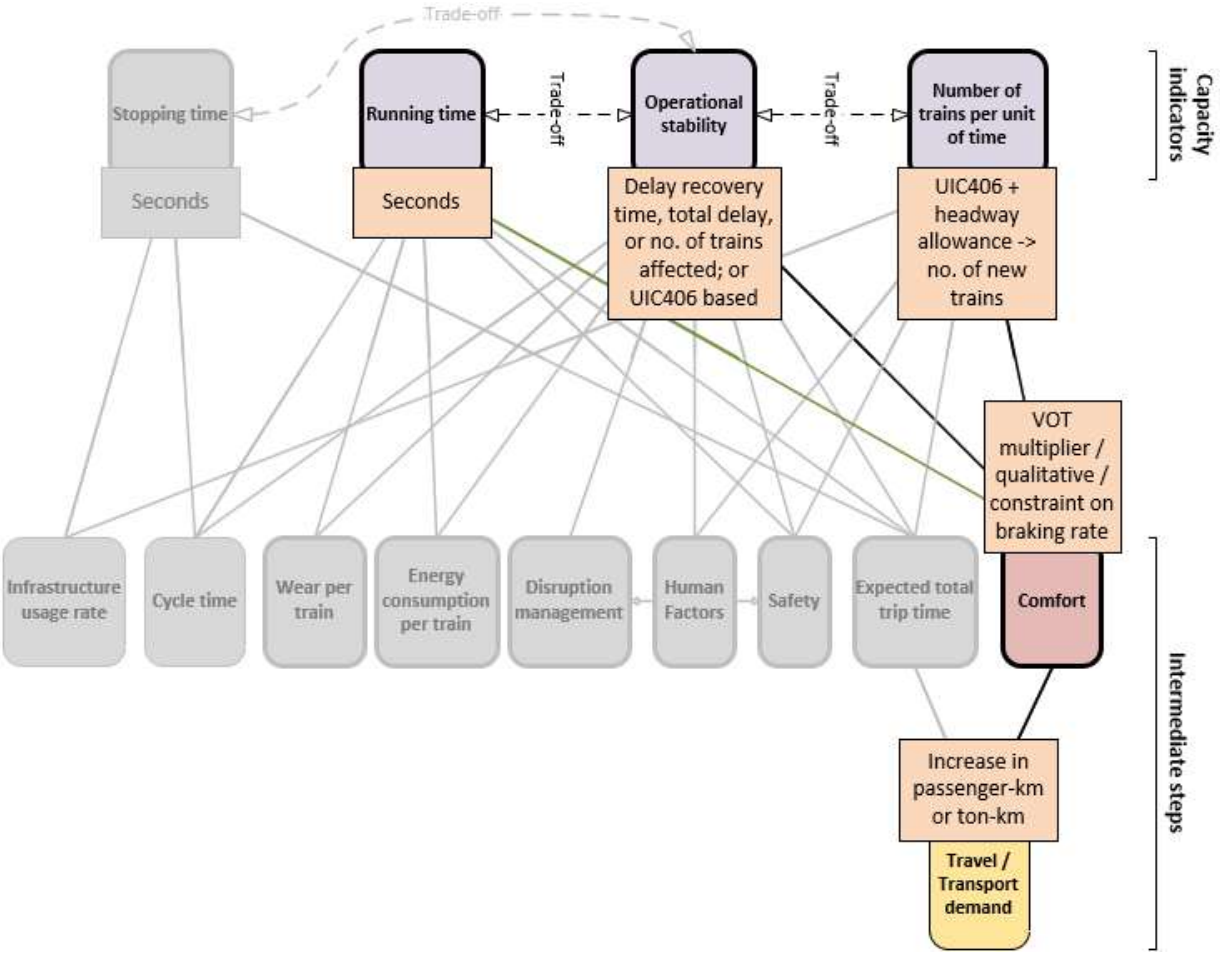


Figure 11: Capacity Indicators to Comfort and Travel/Transport demand

A higher number of trains per unit of time will generally increase comfort. Namely, a higher number of trains per unit of time may increase seating capacity per unit of time. Especially in cases where trains already use the full platform length, an increase in the number of trains per unit of time becomes the only way to increase seating capacity without sacrificing seating comfort.

A higher operational stability will lead to increased comfort for passengers. Namely, with less delays, passengers will on average spend less time waiting at the platform or for delayed trains. Also, they are less likely to find themselves in an overcrowded train resulting from an earlier cancellation or missed connection. Finally, they are less likely to suffer from having to find alternative, less comfortable modes of transport.

Finally, the effect of running time on comfort is endogenous. In other words, there exist both a capacity-related effect from running time on comfort, as well as a potential direct effect of a DATO technique on comfort. Since the variable is endogenous, it deserves caution in analysis.

The capacity effect is that lower running time may result from faster acceleration and braking. As a result, passengers or freight units may prefer smoother driving styles, which may limit the potential capacity benefits in terms of running time. A prominent example of such is tilting technology for trains. While they enable shorter running times, they also enhance the risk of motion sickness (Förstberg, 2000).

The endogenous effect is that certain technologies may limit the jerk experienced during the engagement and release of the throttle or brake. This may smoothen the ride quality up to acceptable levels again. In addition, as demonstrated by Hé et al. (2025) in D32.3, technologies may limit wheel slip occurrence and wheel slip severity, which also improve comfort.

Figure 11 finally shows that comfort is an important input to determine travel / transport demand. This logically follows from the effect comfort has on the generalized cost of travel.

3.3.2 Expected total trip time

The expected total trip time represents the expected time taken when travelling from origin to destination, including time spent off the train. An analogous term for total trip time is door-to-door travel time. For freight, the origin is the production or import location of the goods, and the destination is the location where the goods shall be supplied. The addition of 'expected' captures the stochastic nature of travel. That is, a passenger or freight unit will have a range of potential arrival times at their destination depending on, for example, the probability distribution of delays for that specific journey. Literature commonly refers to the stochastic nature of travel time as travel time reliability (Fosgerau, 2016). This stochastic element is incorporated into the intermediate-step indicator to reflect the impact of operational stability on travel time valuation.

We identify four capacity indicators that affect the expected total trip time. Figure 12 below presents them, including suggested units of measurement.

First, when the number of trains per unit of time increases, then the average waiting time at the platform decreases (Mohring, 1972). As a result, the expected total trip time decreases. One could argue that this benefit is not present for someone that takes a single train from station to station. Indeed, a traveller has information on the scheduled timetable and may adapt their scheduled activities and start their trip such that they arrive at the station platform close to departure. Nonetheless, a low number of departures per unit of time still represents some welfare loss, as the traveller is more likely to spend time to acquire information on the scheduled timetable when

frequencies are lower (Polydoropolou & Yai, 2008; van Oort, 2011) and more likely to err on the safe side and arrive to the platform earlier (de Jong & Fare, 2021).

Second, a higher occurrence rate and a higher size of delays will increase the expected total trip time through its effect on the probability distribution of trip times. Hence, ceteris paribus, an improvement in operational stability will decrease the expected total trip time.

Finally, increases in running time and stopping time straightforwardly increase the expected total trip time. In case of stopping time increases, only the expected trip time of the travellers or goods that remain on the train will increase.

Notably, travellers experience delay time as worse than planned travel time, reflecting the disutility of the unexpectedness of delays (Fosgerau, 2016; Kouwenhoven et al., 2014; Polydoropolou & Yai, 2008). Also, travellers experience time spent standing still as worse than time spent while the train is moving (Hansson et al., 2022; Peftitsi et al., 2023). Due to this, it is important to decompose measurements of the expected total trip time across different phases of the trip.

Figure 12 finally shows that travel demand depends on the expected total trip time, as the overall value proposition of the train relative to other modes of transport (or relative to not making the trip) changes when the expected total trip time changes. More specifically, the opportunity cost of travel due to time spent travelling decreases as the expected total travel time decreases.

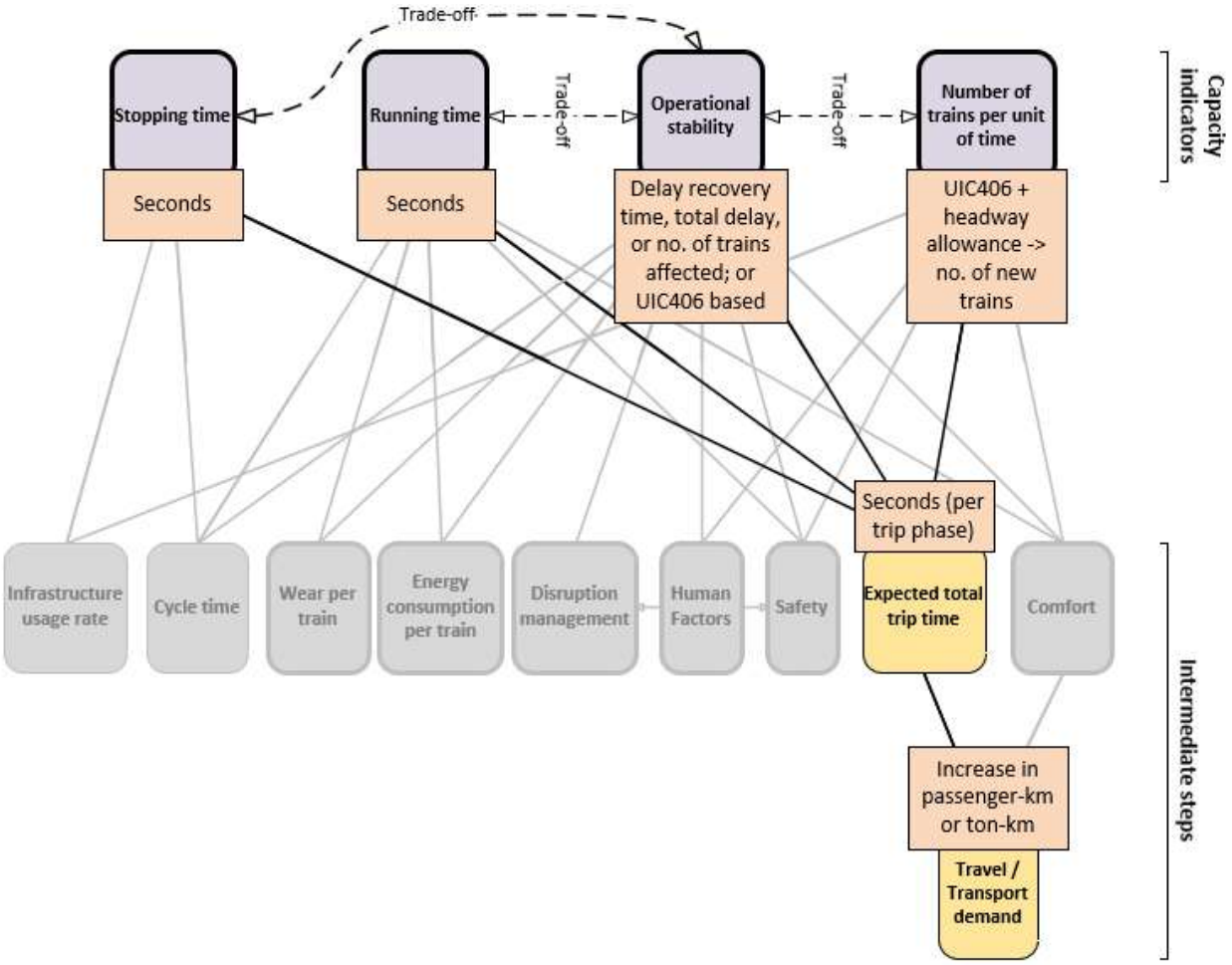


Figure 12: Capacity Indicators to Expected total trip time

3.3.3 Safety, Disruption Management, Human Factors

Safety, Human Factors and Disruption Management are all potentially endogenous variables. We group them together in this subsection because Human Factors also influence the other two. Below, we define them individually, explain their relations to capacity indicators, and explain their potential endogeneity. Figure 13 below summarizes this.

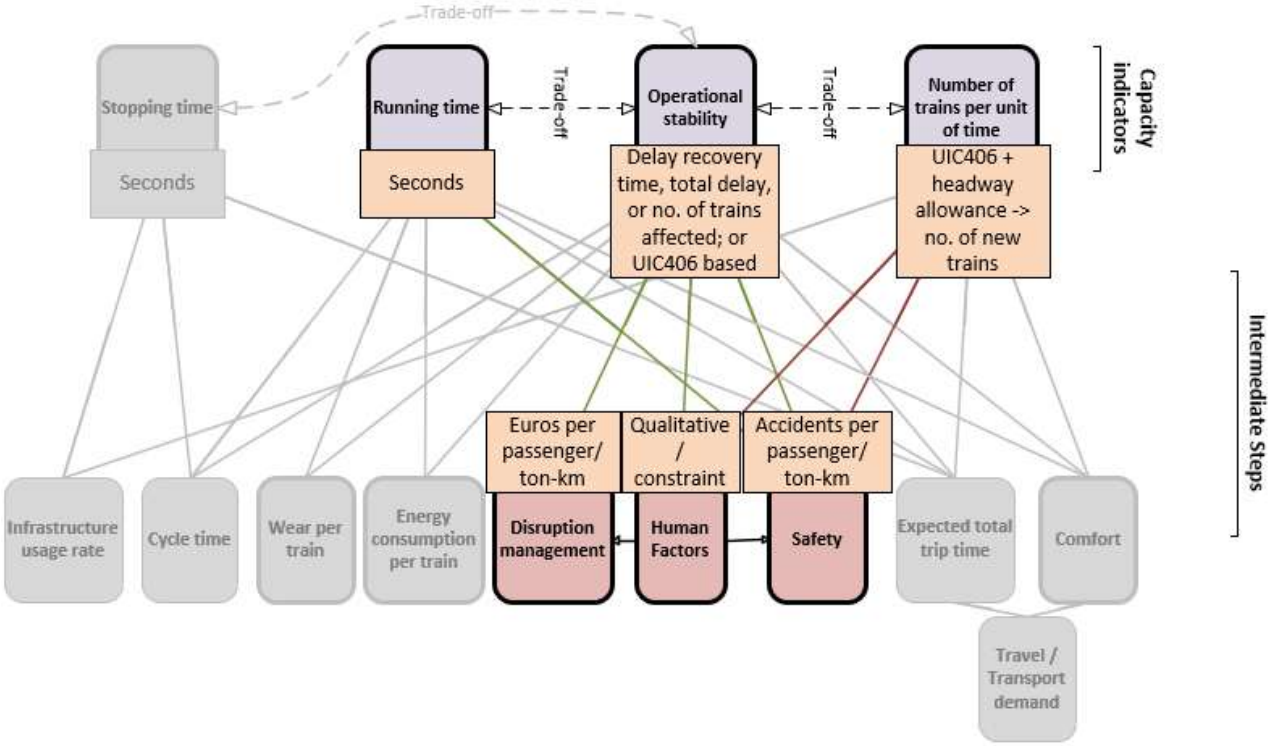


Figure 13: Capacity Indicators to Disruption management, Human Factors, and Safety

3.3.3.1 Safety

Within the railway context, safety represents the risk of injury or material damage to travellers, train staff, freight units, or passers-by. It depends on the risk of human errors and failure of train or track components, coupled with hazards like high running speed or large numbers of at-grade crossings. These might lead to a higher number or higher severity of collisions and derailments, which could lead to injuries or fatalities. A logical resulting unit to use is the number of accidents or a monetary representation of such, per passenger-km or ton-km (ERA, 2024).

We argue that safety has a negative relation to the number of trains per unit of time, a positive relation to operational stability, and a positive relation to running time.

First, a higher number of trains per unit of time may have a negative effect on safety or at least require proportional investment to maintain the contemporary safety level. Namely, trains that operate closer together have a higher theoretical potential to collide with other trains, as well as with road users at level crossings.

Second, a higher operational stability has a positive relation with safety. Namely, trains follow their planned timetable more often and more closely. This decreases the rate of occurrence of unplanned

braking and acceleration actions. Also, in a perturbed state of operations, train drivers and traffic controllers need to do more manual work under larger pressure. This could lead to mistakes that increase safety risks, especially if the train drivers get manual authorisation to pass a stop signal.

Third, if the running time increases, then the average speed of the train decreases. Then, straightforwardly, any accidents that happen may occur at lower speed and have smaller damage potential.

Safety may be endogenous. Specifically, a new policy or technique could alter the safety of railway operations directly, in addition to an effect on the spatio-temporal behaviour of trains through operational stability and the number of trains per unit of time. For example, a new signalling system that uses dynamic braking curves, such as ETCS, may be safer than some multiple aspect signalling system with no speed control below 40 km/h speeds, as the rate of overshooting a red signal would strongly decrease. As a result, a policymaker that is happy with maintaining a previous safety level may accept an increase in the number of trains per unit of time, a decrease in operational stability, or a decrease in running time, at least as it pertains to safety. Oppositely, a technology that decreases safety directly may force a policymaker that prioritizes retaining old safety levels to increase operational stability, increase running times, or decrease the number of trains per unit of time. Indeed, we establish operational stability, running time and safety as complements, while the number of trains per unit of time and safety are substitutes.

3.3.3.2 Disruption management

We specify disruption management as the resources used to mitigate the negative effects when trains get delayed or cancelled. These include direct costs incurred to transport crew, goods and/or passengers to their destination by alternative transport, as well as refunds issued to those affected. They may also include ex ante disruption management measures, such as having emergency staff or rolling stock on hold to quickly fill up gaps in the crew and rolling stock cycles, as well as having a sizeable customer service, traffic management, and/or ad hoc train planning department. Consequently, we propose to measure disruption management as the sum of costs for both ex ante and ex post types of disruption management per passenger-km or ton-km.

Regarding changes in the spatio-temporal behaviour of trains, we relate disruption management to operational stability. Specifically, when delays occur more frequently or are more severe, the occurrence rate and severity of required disruption management activities also increase. Note that for marginal improvements in operational stability, this effect will likely be quite low.

Disruption management may be endogenous. Namely, a new technology or policy could alter the required disruption management efforts directly, in addition to the effect through operational stability. For example, a technology that removes the need for certain onboard crew will lower the need for emergency staff on hold to fill those onboard crew roles. On the other hand, with driverless operation, there might be an increase in the required emergency staff for issues that need to be handled manually. Another example is that a more automated traffic management may be able to handle more or worse disruptions with the same number of traffic managers. As a result, a policymaker that is happy with returning to a previous level of disruption management efforts may accept a decrease in operational stability. Consequently, we posit operational stability and disruption management as complements.

3.3.3.3 Human Factors

We specify human factors as a catch-all term for operational behaviour by drivers, operators and staff involved in the operation of a train. This includes performance and limitations of human actors in railway operation, such as train drivers, maintenance staff, and traffic controllers.

The causal effect of capacity indicators on human factors is that working pressure decreases when operational stability improves, while working pressure increases when the number of trains per unit of time increases. This may hold both for trackside staff as well as onboard staff.

For an extensive description of Human Factors in the context of railway operations, we refer to D32.4 (Lo et al., 2026). They outline an exhaustive list of human factors aspects, framing human factors as a risk when introducing a new technology or policy. More concretely, they argue that the effective introduction of a new technology or policy requires training, operational change management, good hardware and software design with the human in mind, and other mitigation procedures, with the goal of mitigating human errors and negative impacts on working conditions. Hence, we define human factors as either a constraint on the potential capacity gains, or in absolute sense measured qualitatively (see D32.4; Lo et al., 2026).

Indeed, if one does not implement a new technology or policy with human factors in mind, then they may pose a constraint on the efficacy or feasibility of new policies and technologies. For example, if one implements an automated driving technology without considering the effect on deskilling and boredom of the driver, then operations may become less safe. Similarly, if one implements an automated driving technology without considering the effect on working pressure for the traffic manager through altered operational tasks and roles, the job of a traffic manager may become less attractive. Hence, a stakeholder that is highly concerned with safety or working conditions may decide that the technology may only be rolled out partially, if at all. Per this logic, human factors are endogenous.

3.3.4 Energy consumption per train, Wear per train

Energy consumption per train and wear per train are both potentially endogenous variables. We group them together in this subsection because they relate similarly to capacity indicators. Below, we define them individually, explain their relations to capacity indicators, and explain their potential endogeneity. Figure 14 below summarizes this.

3.3.4.1 Energy consumption per train

Straightforwardly, the energy consumption per train may be measured in kWh an average train consumes per unit of travel distance. It relates positively to both operational stability and running time. Since sub-task 32.2.1 of the Grant Agreement for this Work Package goes out of its way to mention the goal of *“analysis of the potential of energy-saving benefits (adopting automated driving styles)”*, we devote special attention to it here.

The relation between running time and energy efficiency is as follows. The total running time may exceed the technical minimum running time through a running time allowance, as defined in section 3.1.4 above. Following Scheepmaker & Goverde (2015), this planned running time allowance (or supplement) allows trains to adopt a more energy-efficient driving strategy than the one with maximum effort towards the next station. Indeed, the driving strategy has a large impact on the energy consumption of a train. Scheepmaker et al. (2020b) define a set of four driving strategies that encompass four relevant extremes: (1) minimum time train control (MTTC), (2) reduced maximum

speed (RMS), (3) maximum coasting (MC), and (4) the energy-efficient train control (EETC). Figure 15 below shows these four driving strategies in a speed-distance diagram.

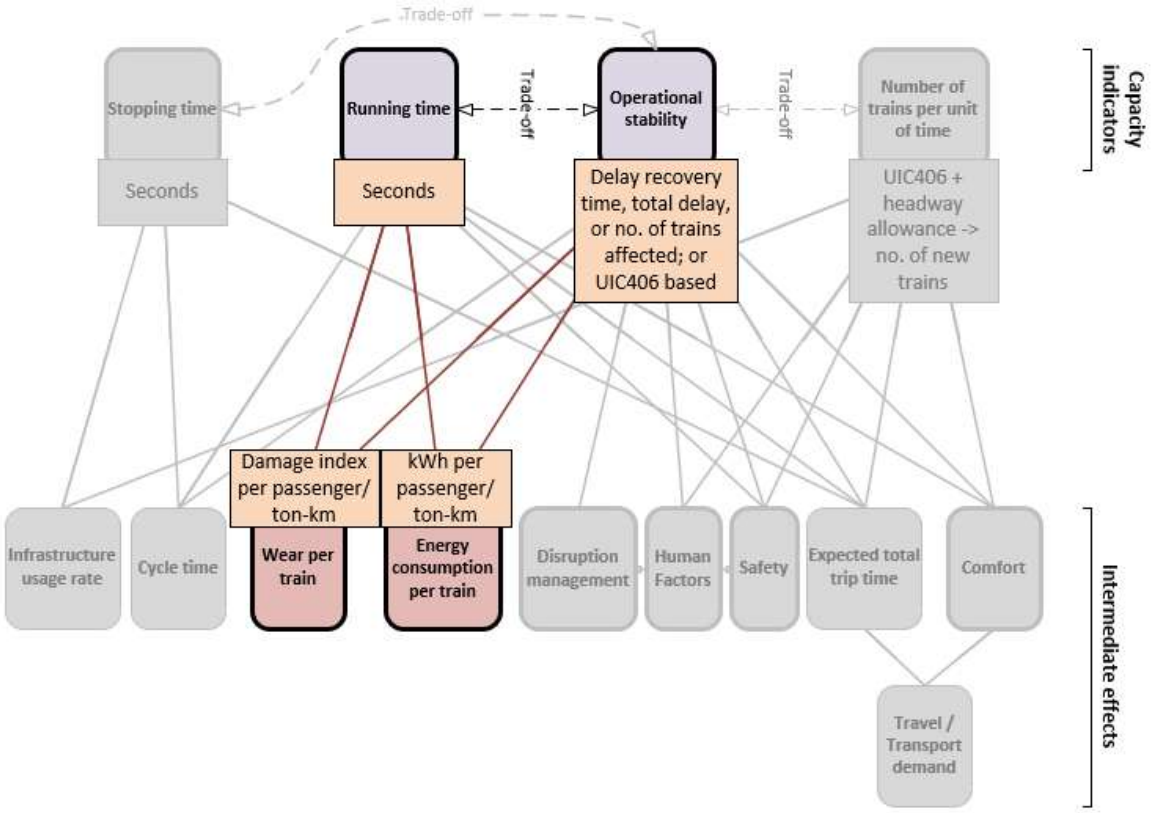


Figure 14: Capacity Indicators to Energy Consumption per train and Wear per train

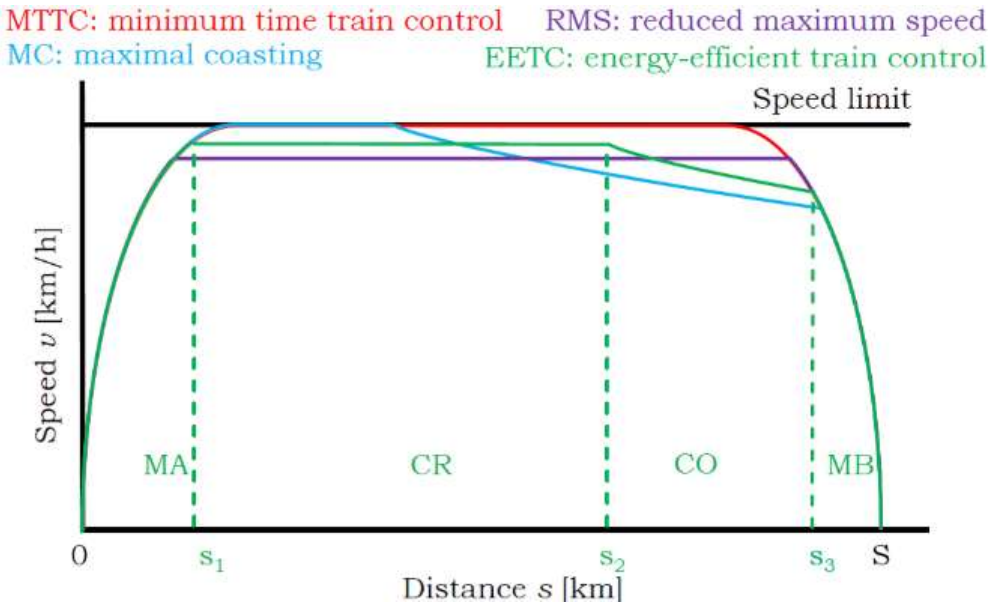


Figure 15: Speed-Distance diagram of different driving strategies

Note: figure shows speed-distance profiles for a simple zero gradient track without varying speed limits. Driving regimes MA = maximum acceleration, CR = cruising, CO = coasting, MB = maximum braking.

The MTTC driving strategy aims to minimize total running time and is equal to the technical minimal running time. In such, it arrives too early when a train is on time and the timetable has running time allowance. MTTC is not energy-efficient in those circumstances. In this driving strategy, the train runs as fast as possible by the driving regimes maximum acceleration (MA), cruising (CR) at the speed limit and maximum braking (MB).

This is the strategy that delayed trains aim to follow. Therefore, a higher operational stability can decrease the (expected) energy consumption per train, as trains will more often retain the ability to use an energy-efficient driving strategy towards the next station instead of needing to run at the technical minimal running time to make up for a delay. A second effect of operational stability on energy consumption per train runs through the occurrence rate of unplanned braking and accelerating actions, as these cost more energy per unit of distance when compared to cruising or coasting.

The RMS, MC and EETC driving strategies are all eco-driving strategies. All strategies follow maximal acceleration, as this is energy-efficient due to high traction efficiency, heavy weight and low rolling resistance of trains. RMS uses the running time allowance to cruise at reduced maximum speed, MC uses the running time allowance to coast as long as possible, and EETC is the energy-optimal solution, which may be equal to RMS, MC, or an intermediate of the two depending on the railway line and train of interest.

It follows that higher running time allows trains to adopt a more energy-efficient driving profile, as they can start coasting (earlier) in anticipation of a necessary speed decrease or run with a lower maximum cruising speed. It is worth noting that the energy saving potential of higher running times has marginally diminishing returns. That is, the first seconds of extra running time add more energy saving potential than the same number of seconds added to a run that is already running far above its technical minimal running time. This is because some frictional forces experienced by trains increase exponentially in the speed of the train, while time and speed have a linear relation. A practically irrelevant nuance is that the positive relation between running time and energy efficiency inverts when the train has extremely large running time as tractive energy then becomes dominated by other time-increasing energy needs of the train (lighting, heating, etc.).

The application of driving strategies differ across countries. For example, the Swiss Federal Railways (SBB) aim to apply RMS (Graffagnino et al., 2019), while the Dutch Railways (NS) aim to apply the MC driving strategy (Scheepmaker & Goverde, 2015; Luijt et al., 2017). In practice, all three energy-efficient driving strategies come with computational challenges, such as finding the optimal cruising speed (for RMS), optimal coasting starting point (for MC), and optimal combination of one or both (for EETC) (Scheepmaker et al., 2020b). Hence, trains and their potential human drivers may require digital assistance to carry them out. We expand on this in Chapter 4 below when discussing Connected Drive Advisory Systems (C-DAS) and ATO.

It follows that techniques may enable energy-efficient driving strategies without altering the capacity indicators directly. Namely, at the same scheduled running times and with the same timetable allowances thus the same level of operational stability, a more energy-efficient outcome may be reached simply by applying a more energy-efficient driving strategy. As a result, a policymaker that is happy with returning to a previous level of energy consumption per train may suddenly be able to decrease operational stability or running time through lower running time allowances. Indeed, we posit that both running time and operational stability are substitutes when one defines energy consumption per train as such a variable where more equals worse.

Note that a better outcome for passengers and freight would be lower running times, meaning that in relevant terms, there is a trade-off between decreasing running times and improving energy efficiency. This relation again highlights the existing trade-off between lower running times and improved operational stability.

Appendix A explains and contextualizes the four different driving strategies in more detail as part of a self-contained analytical study. This study calculated actual potential energy consumption decreases associated with them as one moves from MTTC to RMS, then MC, then EETC, for several representative rolling stock types used by the Dutch railways (NS).

3.3.4.2 Wear per train

The physical interaction between wheels and rails leads to wear of (1) the rolling components in the train, most notably its wheel surfaces, and (2) the rails, through wear-induced squats and wheel burns. Deliverable 32.3 of this Work Package (Hé et al., 2025) studied the influence of wheel slip ratios on wear of the rails, arguing that such wheel slip occurrences are the core cause of severe rail wear.

From this, we infer that there is a negative relation between operational stability and wear per train. Namely, with a higher operational stability, trains follow their timetable more often and more closely. This decreases the rate of trains running as fast as possible to make up for delays, as well as decreasing the rate of occurrence of unplanned braking and acceleration actions. Both decrease wheel slip occurrence.

Second, we infer that there is a negative relation between running time and wear per train. Concretely, a higher running time implies lower travel speeds. This decreases the forces exerted on the railhead and on some traction and braking components, both directly through lower friction and indirectly through less wheel slip occurrence by getting the opportunity to apply less traction or braking force.

As Deliverable 32.3 (Hé et al., 2025) describes, technologies may decrease wheel slip occurrence directly, too, with the concrete example of improved automated traction control. This means that wear per train is endogenous. In other words, in response to such a technology, a policymaker that is happy with a certain established level of wear per train may decrease running times or operational stability somewhat. However, the policymaker can also choose to cash in the direct wear benefit.

Towards the end of Deliverable 32.3 (Hé et al., 2025), Chapter 4 shortly links wear and business outcomes. They explain the different types of damages wheels and rails may suffer, citing a model that relates track damage mechanisms to maintenance costs (Smith et al., 2017) which distributes track wear into track settlement, rolling contact fatigue, and wear. They measure wear through a quantitative damage index, which means one may measure changes in wear through a direct percentage increase or reduction in relative wear rations between scenarios (Hé et al., 2025). We copy this as a unit here.

3.3.5 Cycle Time

We define cycle time as the minimal trainset cycle time, that is, the time it takes to cycle one trainset from the start of their first journey to the start of their next journey. This includes shunting movements and turnaround time. We cover potential economic and financial effects of the related concept of timetable cycle time – the time it takes for a timetable pattern to repeat itself – through expected total trip time.

As Figure 16 below shows, we straightforwardly define cycle time in seconds and relate cycle time one-to-one to the capacity indicators *Running time* and *Stopping time*. In addition, we relate cycle time to operational stability. Specifically, if trains often suffer delays, then the required cycle times to run a stable timetable need to be higher. That is, generally, operators schedule trains to reach their destination early enough to be able to start their next trip on time. The success rate of carrying out such a scheduled trip sequence on time need not be one hundred percent, but there exists a context-dependent optimal success rate. Below this rate, higher cycle times become rational to be able to more often start the next trip on time and prevent (partial) trip cancellations or delay propagation between journeys. Thus, higher operational stability will improve the success rate of starting the next trip on time, allowing for a decrease in cycle time.

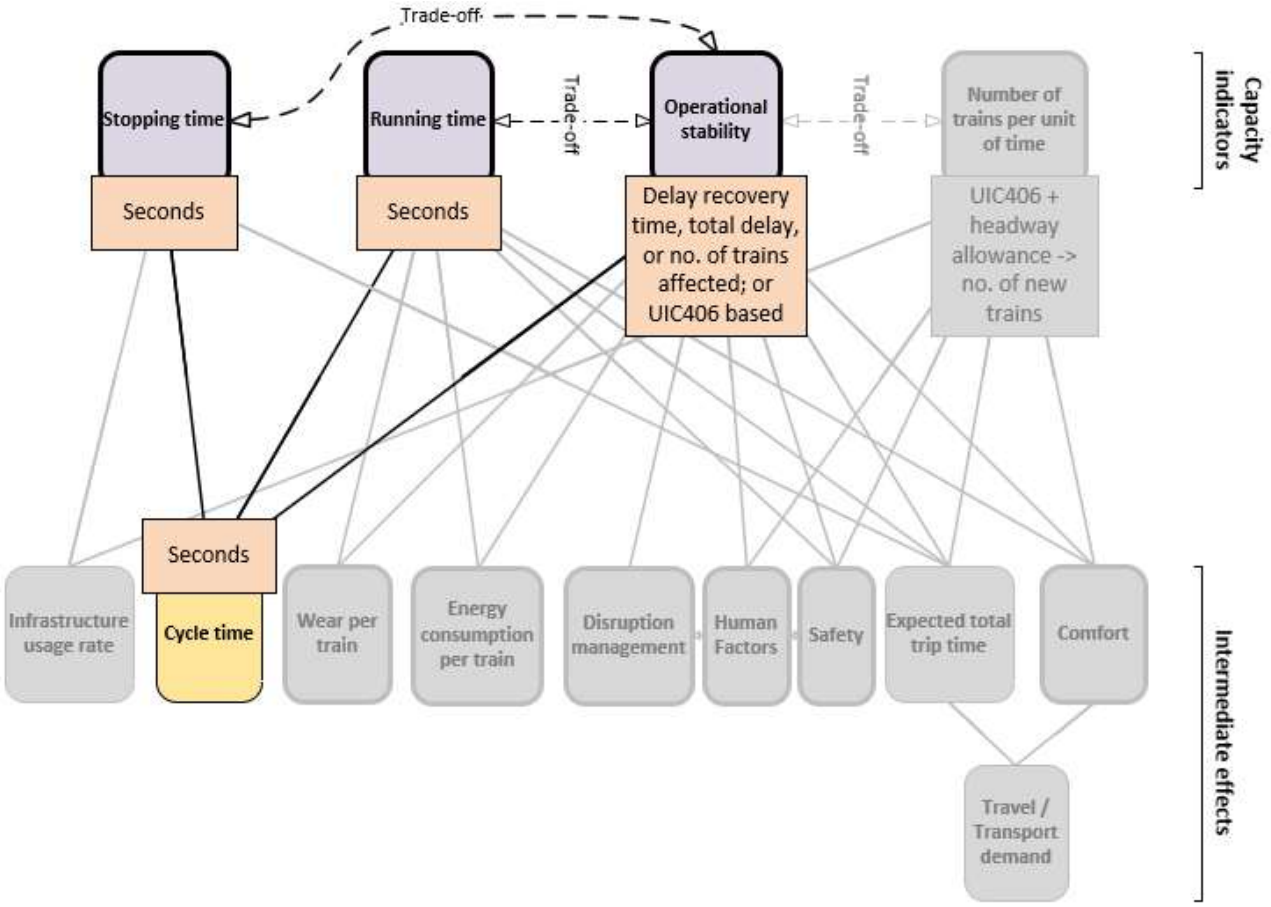


Figure 16: Capacity Indicators to Cycle Time

3.3.6 Infrastructure usage rate

Infrastructure usage rate represents the frequency and severity of usage of the track itself. To calculate track access charges, one often represents this by the number and type of trains, their speed or passed weight in ton-km, and their number of axles, all per unit of time. The infrastructure usage rate is a necessary intermediate step to measure before further calculation into track access charges per Directive 2012/34/EU (European Parliament and Council, 2012).

We posit two links between capacity indicators and infrastructure usage rate: from the number of trains per unit of time and from stopping time. If the number of trains per unit of time goes up, then the infrastructure usage rate will go up. A longer stopping time means trains take more time occupying tracks at a yard, depot or station track. The usage of the tracks in the yard and during station stops is often a cost for the train operating company. Figure 17 below shows these links within our interface matrix.

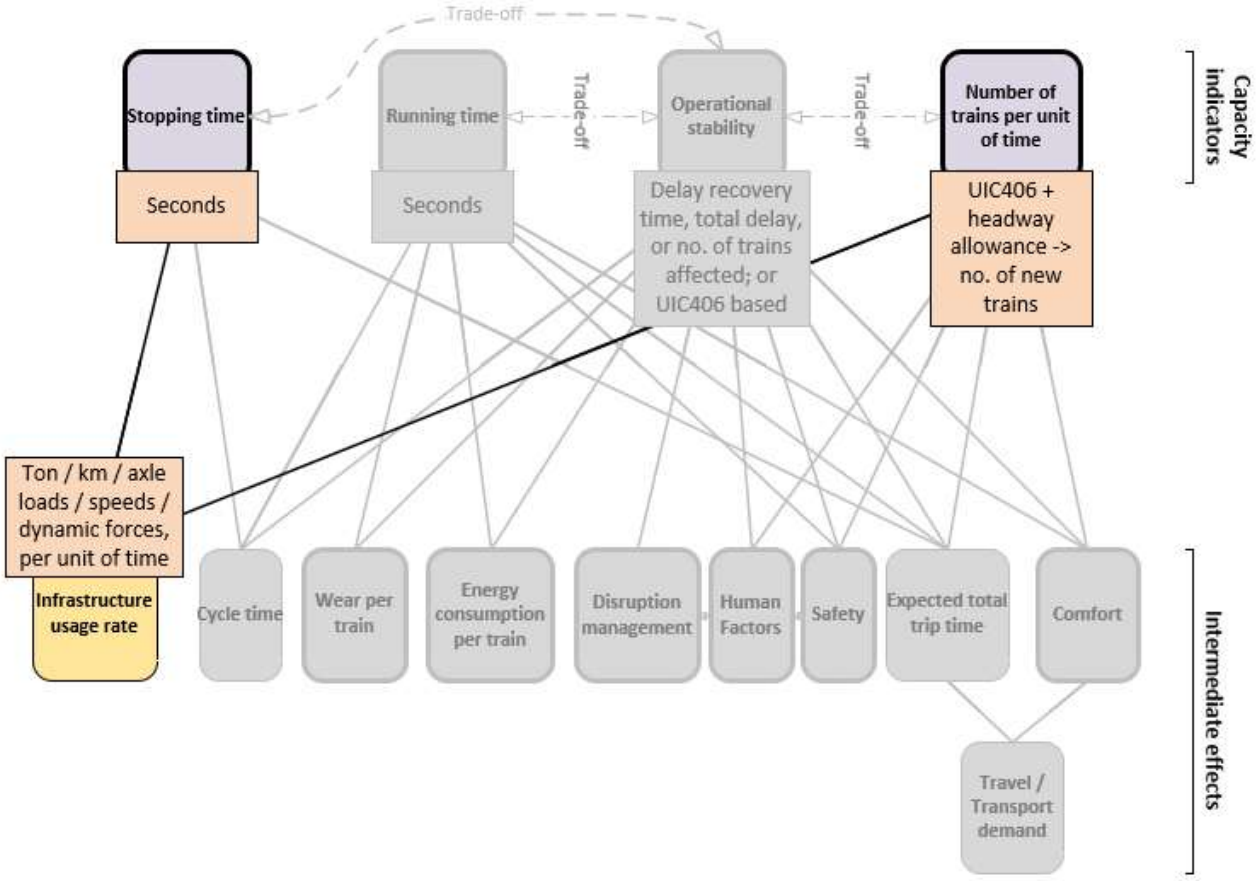


Figure 17: Capacity Indicators to Infrastructure usage rate

3.4 BuCa Value Indicators

Having defined capacity building blocks in Section 3.1, capacity indicators and their links with capacity building blocks in Section 3.2, and intermediate steps and their links with capacity indicators in Section 3.3, we now present the final list of BuCa value indicators and their links with previous steps in Section 3.4.

We define fourteen BuCa value indicators. We divide them across stakeholders as recommended by the strategic review in Deliverable 32.1 (van den Berg et al., 2026). Table 4 below defines these fourteen value indicators, including suggested units of measurement.

BuCa Value Indicator	Definition	Unit
	(Society / Economy)	
Other welfare effects	Societal benefits or costs that are not directly captured by other effects, such as social inclusion and mobility, regional development spillovers, health/safety impacts of modal shifts, and congestion relief on other modal networks because of modal shifts	Euros per year, valued using economic study results or qualitatively
Agglomeration effects	Economic productivity changes that occur when economic actors are brought closer together due to knowledge spillovers, economies of scale, and market expansion	Euros per year, valued using economic study results or a multiplier on Value of travel time
Passenger welfare	Utility resulting from travel conditions	Euros per year, measurable through consumer surplus from economic studies or qualitatively
Value of travel / transport time	Generalized perceived cost of time spent travelling (passengers) or being transported (goods). Also incorporates welfare gains by new travellers in scenarios with increased travel demand	Euros per year, valued using economic study results. Welfare gains for new passengers subject to 'rule of half': existing travellers enjoy the full size of the welfare gain from travel cost reduction, new travellers assumed to gain half of this welfare value
External environmental effects	Changes in air and noise pollution, greenhouse gas emissions, and other environmental and ecological impacts	Euros per year value of emitted pollutants, valued using economic study results and future emission cost scenarios
	(Train Operator / Transport Authority)	
Ticket sales, economies of scale	Revenue changes and per-unit cost changes that depend on the scale of operations	Euros per year
Fleet size of rolling stock	Capital cost of all rolling stock	Euros per year (depreciation)
Vehicle maintenance	Cost of maintaining all rolling stock	Euros per train-km or per year
	(both Train Operator / Transport Authority and Infrastructure Manager)	
Staff costs	Costs for all staff	Euros per year
Labor conditions	Quality, safety and fairness of the working environment for staff	Qualitative, may also estimate reduction in sick leave and accidents (and associated productivity gains in euros per year)
	(either Train Operator / Transport Authority or Infrastructure Manager)	
Energy Costs	Cost of energy consumed by trains	Euros per train-km

	(Infrastructure manager)	
Infrastructure access fees	Revenue from charges paid by train operators for usage of the railway track	Euros per train-km or ton-km
Infrastructure investments	Capital costs for new or upgraded infrastructure	Euros per year (depreciation)
Infrastructure maintenance	Cost of maintaining the railway track and related assets	Euros per km of track per year

Table 4: BuCa Value Indicators

One can measure all fourteen Value Indicators in euros, allowing one to apply quantitative cost-benefit analysis methods on the results. Indeed, the proposed units in Table 4 correspond to standard cost-benefit analysis guidelines and literature (European Commission, 2014; Small & Verhoef, 2007).

However, many of these measurements require dedicated project-specific economic research and shared financial data by the associated stakeholders. This far exceeds the scope of the current project. Hence, we note that not all Value Indicators will be quantified in the application of our interface matrix on the capacity simulations from FP1-WP9, described in Chapters 5-7.

The rest of this subsection describes the fourteen BuCa value indicators and their links to previous Intermediate Step or Capacity indicators. We divide this into sections depending on the stakeholder that effects on the BuCa value indicators would accrue to.

3.4.1 BuCa Value Indicators – Society/Economy

Figure 18 below shows the part of the interface matrix that describes effects from intermediate steps, described in Section 3.3, on BuCa value indicators that accrue to society and the economy at large. It also includes one direct link from a capacity indicator to a BuCa value indicator (number of trains per unit of time to external environmental effects), as we do not explicitly define intermediate steps needed to clarify this link.

3.4.1.1 Other welfare effects

The Other Welfare effects indicator captures societal benefits and costs that are not directly reflected in the primary transport user impacts or in external environmental impacts but nonetheless contribute to overall social welfare. We start with a description of this simply due to the order of indicators from top to bottom in the interface matrix. These effects include broader outcomes such as improvements in social inclusion and mobility, regional economic spillovers resulting from enhanced accessibility, and health and safety impacts associated with shifts toward public transport and active travel. In addition, modal shifts to trains may reduce congestion on competing road networks, generating indirect benefits for remaining road users.

Although such effects can be more difficult to quantify consistently than direct travel time or cost changes, the transport economics literature has started to recognize them as important components of the total welfare impact of mobility interventions (Geurs et al., 2009; Venables, 2016). Accordingly, we suggest measuring it in euros per year. However, given limited research resources, one may also choose to express these effects qualitatively.

We identify both a direct effect from expected total trip time on other welfare effects, as well as an indirect effect through changes in travel demand. Aside from through total trip time, travel demand may also increase due to improvements in comfort. This distinguishes other welfare effects for both existing and new train users.

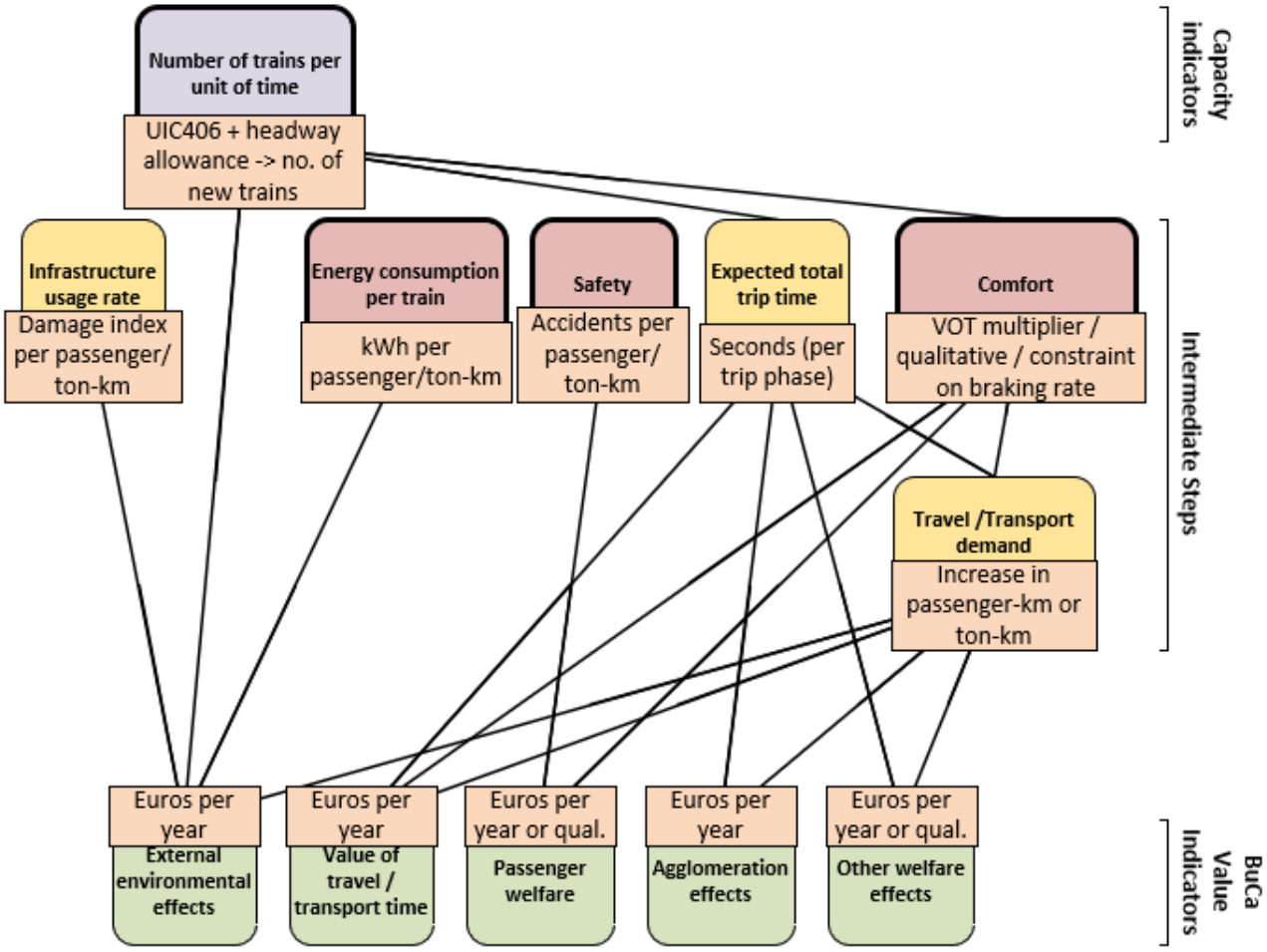


Figure 18: Intermediate steps to BuCa Value Indicators for Society

3.4.1.2 Agglomeration effects

Agglomeration effects are welfare gains from enhanced productivity that arise when firms and workers are located close to each other. Economic mechanisms for these effects are knowledge spillovers and input-output linkages that generate local economies of scale (Krugman, 1991; Marshall, 1920). Within the context of railways, a decrease in the generalized cost of travel puts firms and workers closer to each other, which leads to improved accessibility (Hansen, 1959), and this is associated with a wide range of economic benefits that result from increased productivity such as higher economic development and higher income levels (Donaldson & Hornbeck, 2016; Rojas et al., 2026).

Within transport project appraisal, an economic analysis that ex ante quantifies the complex underlying economic effects is often not feasible, and the debate instead focuses on which multiplier on the Value of Travel/Transport Time effect to choose as rule-of-thumb. A common value in the

literature at this point is a multiplier of 0.15. That is, existing transport appraisal guidelines state that agglomeration effects have a size of roughly 15% of the direct value of time savings for existing travellers (Gibbons & Graham, 2019).

Per Figure 18 above, we identify both a direct effect from expected total trip time on agglomeration effects, as well as an indirect effect through changes in travel demand. Aside from through total trip time, travel demand may also increase due to improvements in comfort.

3.4.1.3 Passenger welfare

We define passenger welfare as the quality of the trip that passengers experience in terms of seat quality, ride quality, safety, and disutility from crowding and delays that are not captured in the value of travel time. More theoretically, we define it as the qualitative component of the generalized perceived cost of travel. As explained in Section 3.3.1 above, travel comfort in all its facets is an important determinant of passenger welfare, and a salient topic of research in the transport appraisal literature (Small & Verhoef, 2007; Warffemius et al., 2016; Kouwenhoven & de Jong, 2018). While this does offer some guidance in measuring welfare in euros, we suggest that qualitative measurement may also be appropriate given limited research resources.

3.4.1.4 Value of Travel / Transport time

The Value of travel (passenger) or transport (freight) Time (VOT) measures the time component of the generalized perceived cost of travel. A broad literature on the quantification of this welfare effect exists, in accordance with it often being the strongest welfare effect present in transport project appraisal (de Jong & Kouwenhoven, 2020; Mackie, 2001).

In Cost-Benefit Analysis guidelines for transport projects, VOT is a standard input for converting time savings into monetary benefits. They are periodically updated and may be divided per mode of travel (de Jong & Kouwenhoven, 2020). The economic literature provides several approaches to infer values of travel time from behaviour and preferences, grounded in utility theory (Shires & de Jong, 2009). Wardman et al. (2016) present a meta-analysis of values of travel time in Europe, showing differences depending on the data collection method and across countries. Nonetheless, values usually range between 6 and 12 euros per hour on for the average travelled hour in Europe.

The value of travel time is not the same across modes, trip types, and travel time categories. Specifically, commuter and business trips have a higher value of travel time than leisure trips, with long-distance business trips having an especially high multiplier (Wardman et al., 2016). Train trips generally have a slightly lower average value of travel time than car trips (de Jong & Kouwenhoven, 2020) because train trips still allow for certain productive activities to be carried out during the trip. The link from Comfort to VOT exemplifies this. Indeed, the comfort level determines the extent to which passengers can use their travel time productively or pleasantly, thereby affecting the value of travel time (Kouwenhoven & de Jong, 2018; Kroes & Koopmans, 2014) as well as the disutility suffered during delays (van Hagen & de Bruyn, 2015).

In addition, we straightforwardly link the expected total trip time with VOT. Nonetheless, this link requires special attention. Namely, travel time spent on delays has a higher perceived VOT when compared to planned VOT. The reason for this is that delays may conflict with other planned activities (Fosgerau, 2016; Kouwenhoven et al., 2014; Polydoropolou & Yai, 2008). Also, travellers experience time spent standing still as worse than time spent while the train is moving (Hansson et al., 2022; Peftitsi et al., 2023). The reason for this is a time perception bias in travellers.

Due to this, it is important to decompose measurements of the expected total trip time across different phases of the trip, and to multiply delay time and stopping time with appropriate multipliers. Warffemius (2015) suggests a factor 3 to 4 for delay VOT when compared to the timetabled VOT, while experts at the ProRail capacity management department recently suggested multiplying stopping time by a factor of 1.06, as well as adding one minute worth of VOT in addition to the actual stopping time for every scheduled stop.

Finally, we identify an effect of travel/transport demand on VOT. Namely, when a project reduces generalized travel costs, not only do existing users gain consumer surplus from the trips they would have made anyway, but new travellers induced by lower costs also gain surplus. Standard transport CBA methods prescribe this through a "rule of half" (Small & Verhoef, 2007), which mirror the UIC406 workaround presented in Figure 8. Specifically, the rule reflects a linear approximation of the demand curve between the initial and new travel equilibrium, implying a welfare gain equal to the ½ × the change in VOT × the change in demand. Ergo, using models that predict new passengers or freight units according to changes in expected total trip time, one can then multiply this by half of the change in VOT for an existing passenger or freight unit.

3.4.1.5 External environmental effects

External environmental effects capture the negative welfare effects from emissions that result from transport activities, imposing costs on society beyond what users directly pay (Small & Verhoef, 2007).

For railways, negative external environmental effects exist mostly through air and noise emissions. Van Essen et al. (2019) devote several chapters to the economic quantification of air pollution, climate change, and noise emissions.

We identify a direct link from the number of trains per unit of time on external environmental effects to represent the quantity of such emissions resulting from rail transport. Also, we identify a direct link from the infrastructure usage rate on external environmental effects to represent the frequency of such emissions.

Nonetheless, external environmental effects in rail transport are much lower than for a comparable passenger or freight quantity transported for road or aviation (van Essen et al., 2019; EEA, 2021). Therefore, the link from travel/transport demand to external environmental effects likely dominates, as these represent some degree of modal shift from more polluting modes of transport.

Finally, a lower energy consumption per train may lower greenhouse gas and air pollutant emissions depending on the fossil fuel extent of the energy mix used to power the train. Even if the energy used for rail transport is completely renewable, such renewable energy could otherwise be used for other purposes. In such, a lower energy consumption per train may be good for the environment.

Note that one may also consider the potential of abated large-scale new railway track construction to satisfy demand, which DATO techniques may prevent the necessity for. In such case, external environmental benefits become especially sizeable not just in abated greenhouse gas and noise emissions associated with the construction of new railways, but also in abated land use externalities.

3.4.2 BuCa Value Indicators – Train Operator / Transport Authority

Figure 19 below shows the part of the interface matrix that describes effects from intermediate steps, described in Section 3.3, on BuCa value indicators that accrue to the train operator, in some European countries more aptly described as the transport authority.

A contextual note is that some of the value indicators here describe broad cost categories for the train operator, but the inclusion here only pertains to capacity induced effects. We did not consider other drivers of costs. For example, in ATO implementation, the operator might incur costs to build hardware and software components into their rolling stock, incur costs to train their personnel, or save costs by removing the need for some personnel. These are all direct effects that do not stem from capacity, and the interface model we present in this Deliverable does not seek to include them. Instead, the effect on the BuCa value indicator 'fleet size of rolling stock' due to ATO here comes purely from a capacity effect. Specifically, it may come from reductions in running time or improvements in operational stability, which could reduce the cycle time, which could then reduce the fleet size of rolling stock. For an overview of all direct cost categories, we refer to D32.1 in this Work Package (van den Berg et al., 2026).

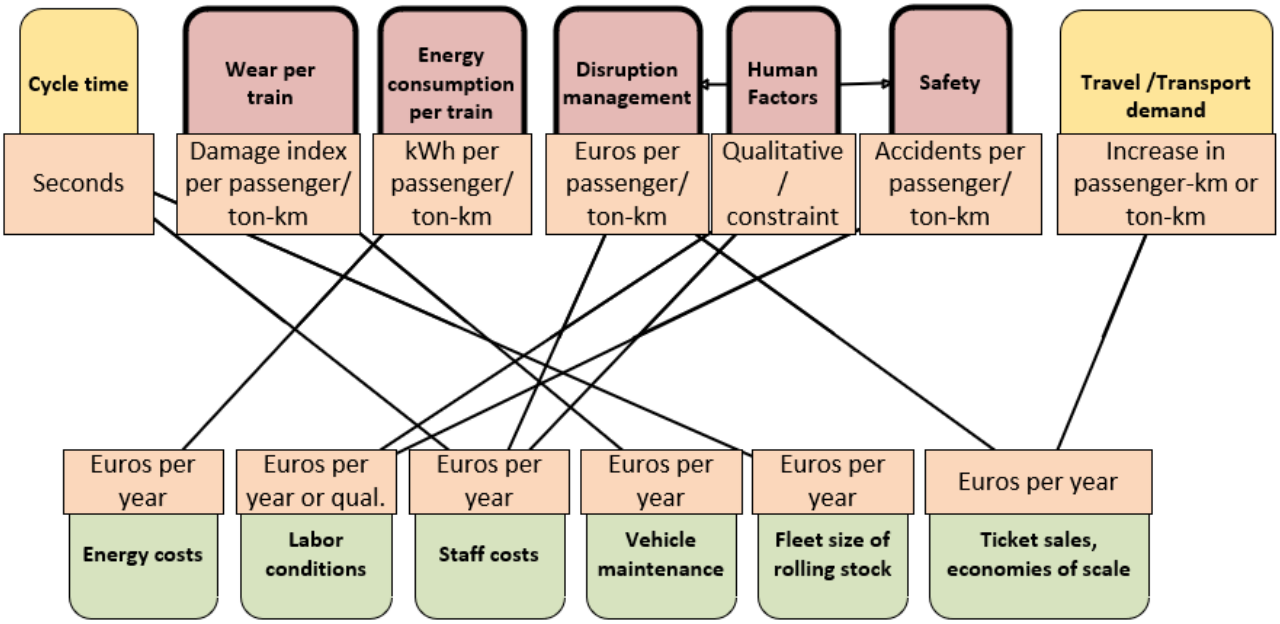


Figure 19: Intermediate steps to BuCa Value Indicators for Train Operator / Transport Authority

3.4.2.1 Ticket sales and Economies of Scale

This category captures the marginal profit per passenger or freight unit. It follows from direct revenue from train ticket sales as well as the cost efficiencies that arise from economies of scale. We reason that more tickets (passengers) or freight slots can be sold when travel / transport demand increases. Similarly, revenues can increase when the operator can command a higher price for existing seats or freight slots. Note that more passengers in an existing train generally increase profits more than passengers in a new train.

As for scale economies, in railway transport, certain cost inputs – such as personnel, energy, or rolling stock – do not increase proportionally with passenger or freight volumes. Meanwhile, ticket sales do scale proportionally. As a result, transporting larger groups of passengers or greater freight volumes reduces the per-unit cost, enhancing profitability in addition to an increase in revenue.

We also note an effect of disruption management on ticket sales. This is a straightforward effect of train operators having to refund less delays, thus maintaining a higher percentage of their ticket sales.

3.4.2.2 Fleet size of rolling stock

The fleet size should consist of the vehicles needed for the daily operations and a reserve that could be used in case of unexpected events. The required fleet size for the daily operations depends on the vehicle circulation plan, which is dependent on the cycle time. As the fleet size is a cost, the fleet size should be as small as possible. This also has a secondary effect on the required size of the stabling yards and workshops.

Straightforwardly, if the cycle times decrease, then one requires less rolling stock to realize the timetable. This effect only occurs at certain thresholds. For example, especially for short scheduled trips within certain logistical contexts, timetable regularity considerations and infrastructure constraints (e.g., on single track lines) may render it impossible to exploit a marginal improvement in cycle times, as the trains will still have to start their next trip at the same timepoint they did originally.

3.4.2.3 Vehicle maintenance

Vehicle maintenance is a cost for the vehicle owners. The maintenance level is dependent on how much wear or damage occurs over time. A frequent use of the vehicle might result in high wear of the rolling components, while the way the vehicle is used can also impact maintenance costs. For example, other acceleration and braking behaviour of a train affects the condition of the engine and brakes. Hence, maintenance cost will increase if there is more wear on the vehicle. As we established, a lower running time may increase maintenance costs due to harder required braking, but an improved operational stability may lower maintenance costs due to less braking actions.

Note that this does not consider a change in vehicle maintenance costs due to changes in systems on the train that are required for a new DATO concept. These costs are instead considered in the full Business Case presented in Deliverable 32.1 (van den Berg et al., 2026) but are left out of this document since this document only describes effects resulting from altered spatio-temporal behaviour of trains.

3.4.2.4 Staff costs for the Train Operator / Transport Authority

Staff costs, in context of operations for the train operator, represent the time train personnel work. This includes onboard staff activities, including the time of reaching a train and preparation work. It also includes stationary personnel such as terminal workers and indirect staff, which represent management and support staff, training costs, as well as reserve train staff if the direct staff becomes hindered from reaching their next duty on time.

We note two relations between intermediate effects and staff costs. First, if the cycle times decrease, there are less direct staff costs as trains are quicker to finish their full trip from start to finish. Congruously, indirect staff costs will increase. Second, if required disruption management efforts decrease due to higher operational stability, then one requires less reserve train staff as well as less customer service staff. We finally note that there may also be a direct effect of running time on staff costs, if staff schedules run on only part of the full train run, with for example a crew change halfway. We choose not to specify this as a link in the interface matrix as the mechanism is the same as the one through cycle time, as well as to prevent clutter.

3.4.2.5 Labour conditions

Within the context of capacity effects, labour conditions represent job well-being as well as safety. Job well-being and safety improve when there is higher operational stability and hence improved human factors, as train staff has less forced braking actions. However, a higher number of trains per unit of time or lower running times may enhance working pressure or decrease safety, leading to worsened labour conditions. Note that Deliverable 32.4 (Lo et al., 2026) as well as their aggregation into Deliverable 32.1 (van den Berg et al., 2026) extensively describes how proper consideration of human factors and associated treatment programs can help mitigate the risk of worsened labour conditions for ATO GoA2.

3.4.2.6 Energy costs

A change in the energy consumption per train, for example an increase through lower running times or a decrease through improved operational stability, will directly affect energy costs. In most countries, this tractive energy cost accrues to the train operator. Increasing train speeds yields diminishing marginal travel time savings while substantially increasing energy consumption due to the nonlinear relationship between speed and aerodynamic resistance. Nevertheless, in transport appraisal, travel time savings often dominate energy efficiency outcomes, except for contexts of very high speed (airplanes), low VOT (long distance freight), or energy price crises (Corlu et al., 2020).

3.4.3 BuCa Value Indicators – Infra Manager

Figure 20 below shows the part of the interface matrix that describes effects from intermediate steps, described in Section 3.3, on BuCa value indicators that accrue to the infrastructure manager.

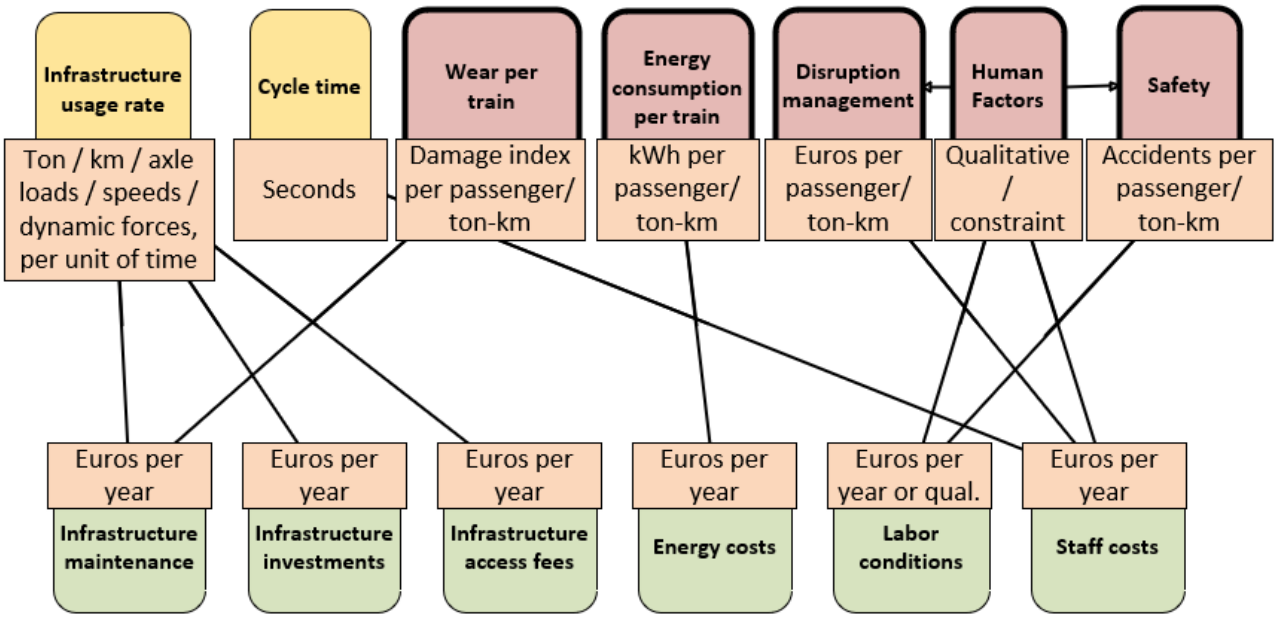


Figure 20: Intermediate steps to BuCa Value Indicators for the Infrastructure Manager

A contextual note is that some of the value indicators here describe broad cost categories for the infrastructure manager, but the inclusion here only pertains to capacity induced effects. We did not consider other drivers of costs. For example, in ATO implementation, wear per train may decrease

due to improved wheel slip prevention outside the scope of any changes in any capacity indicator (see Deliverable 32.3, Hé et al., 2025). This is a direct effect that does not stem from capacity, and the interface model we present in this chapter does not seek to directly measure it, although we note it as reason wear per train is endogenous. Instead, the effect on the BuCa value indicator 'infrastructure maintenance' coming from wear per train becomes purely the effect that stems from reductions in running time or improvements in operational stability, if the policymaker chooses not to trade off the direct wear per train benefit for added capacity.

Another contextual note is that energy costs may not accrue to the infrastructure manager in most European contexts. For example, in the Netherlands, train operators pay for the traction costs. The secondary effect of a slight reduction in electric infrastructure costs may still however accrue to the infrastructure manager.

3.4.3.1 Staff costs

Staff costs, in context of operations for the infrastructure manager, represent the time dispatchers and traffic operators work, including all associated support staff costs, from managers to training costs. It also includes disruption management staff such as incident crews.

As with staff costs for the train operator in Section 3.4.2.4, we note two relations between intermediate effects and staff costs. First, if the cycle times decrease, there are less direct staff costs for dispatchers and traffic managers as trains are quicker to finish their full trip from start to finish. Congruously, indirect staff costs will also decrease. Second, if required disruption management efforts decrease due to higher operational stability, then one also requires less dispatchers and traffic managers, as there are fewer disruptions to process.

3.4.3.2 Labour conditions

Within the context of capacity effects, labour conditions represent job well-being as well as safety. Job well-being and safety improve when there is higher operational stability and hence improved human factors, as train staff have less delays to deal with and less forced braking actions to carry out. However, a higher number of trains per unit of time or lower running times may enhance working pressure or decrease safety, leading to worsened labour conditions. Note that Deliverable 32.4 (Lo et al., 2026) as well as their aggregation into Deliverable 32.1 (van den Berg et al., 2026) extensively describes how proper consideration of human factors and associated treatment programs can help mitigate the risk of worsened labour conditions for ATO GoA2.

3.4.3.3 Energy costs

A change in the energy consumption per train, for example an increase through lower running times or a decrease through improved operational stability, will directly affect energy costs. In some countries, this tractive energy cost accrues to the infrastructure manager. Increasing train speeds yields diminishing marginal travel time savings while substantially increasing energy consumption due to the nonlinear relationship between speed and aerodynamic resistance. Nevertheless, in transport appraisal, travel time savings often dominate energy efficiency outcomes, except for contexts of very high speed (airplanes) or low VOT (long distance freight) (Corlu et al., 2020).

3.4.3.4 Infrastructure access fees

This is the income from infrastructure access fees that train operating companies pay for running a train over the network. These can vary based on time-of-day, railway line, type of train, weight and number of axles. The infrastructure access fee is a cost for the train operator. Since it scales less

than proportionally in the number of travellers, we do not consider it an effect for the operator. Namely, for the operator, these access fees it will be outweighed by Ticket Sales / Economies of Scale by default.

We identify a potential increase in infrastructure access fee revenue and profitability when the infrastructure usage rate increases. Concretely, if more train paths can be sold, the total income of infrastructure access fee for the infrastructure manager will increase. This fee is also a policy parameter for influencing the modal share of rail transport and should normally cover a part of the infrastructure maintenance and renewal costs for the infrastructure manager (IM). Since there is no intrinsic goal for most infrastructure managers to make a profit, a higher infrastructure usage rate could lead to lower access fees in the long term.

3.4.3.5 Infrastructure investments

This indicator represents an interesting category that has the potential to form the entire business case on its own in specific circumstances. Namely, if a studied alternative fulfils all capacity targets and related policy goals while preventing costly new railway lines from being built, then the relative benefits on abated infrastructure investments may quickly go up into the billions of Euros. In other cases, though, a higher infrastructure usage rate may instead come with slight increases in required infrastructure investments to cope with the higher stresses exerted on the tracks.

3.4.3.6 Infrastructure Maintenance

The maintenance of the infrastructure is the responsibility of the infrastructure manager. Reducing the need of maintenance will reduce the cost for the infrastructure owner. We propose two intermediate effects that influence the level of infrastructure maintenance. First, a change in the wear per train will influence track maintenance costs. Second, if more trains per unit of time are running on the same track, the track will deteriorate faster and need to be replaced earlier. Hence, yearly maintenance costs would increase.

3.5 REFLECTION

This chapter presented an interface matrix that relates bare spatio-temporal behaviour of trains with economic and financial effects. This matrix comprehensively bridges the gap between railway capacity literature and economic appraisal literature.

Specifically, we aggregated 10 capacity building blocks into 4 capacity indicators, then translated these into 14 economic and financial indicators (BuCa Value Indicators) through 10 intermediate step indicators. We offered definitions of all indicators, suggested potential units of measurement, and explained the linkage rationales for all indicators. These were strongly rooted within both railway capacity literature and transport economics literature.

The list of four Capacity Indicators corresponds to standard output from specialized microscopic railway capacity simulation software, and the list of 14 BuCa Value Indicators correspond to standard indicators used in economic appraisal, with the potential to satisfy cost-benefit analysis and multicriteria analysis methods, in accordance with the requirements stemming from strategic analysis of the business case literature described in Deliverable 32.1 (van den Berg et al., 2026).

We found the exercise of constructing this interface matrix an engaging one, although we recognize that more senior expertise in particularly railway financial literature, but also in business case and

transport economic appraisal literature, could help sharpen the methodology we put forward. The matrix shall be used with care, as impacts are often interchangeable with decisions to be made about what to allocate potential capacity benefits towards, which constraints from a network-level timetable to satisfy, and which level of detail to pursue in economic analysis.

Altogether, we believe that this interface matrix can elicit a more comprehensive awareness of the scope of all effects that can be caused by changes in our broad definition of railway capacity. This holds for policymakers concerned with economic and financial effects as well as capacity experts. Particularly, we hope the framework can raise awareness among long-term timetable designers that the choices they make on setting capacity building blocks, particularly the allowance times, have vast economic and financial consequences, and could benefit from economic outcome-driven optimization, as well as investment in planning and simulation tools that accurately capture the spatio-temporal behaviour of trains.

In the next chapter, we bridge towards DATO technologies by generating DATO-specific versions of the interface matrix. Afterwards, we apply (parts of) the interface matrix on selected output from capacity simulations from FP1-WP9. Note that the interface matrix returns as part of the methodology described in Deliverable 32.1 (van den Berg et al., 2026), where it forms one of the key inputs for an overall Business Case methodology that also explicitly considers direct costs and human factors effects in addition to capacity effects.

4 DATO TECHNIQUES

For a DATO Business case, the capacity effects of DATO techniques form an essential part. To determine which DATO concepts are relevant to the business case (format), we examined the concepts being developed within R2DATO. The flagship defines DATO techniques as Digital Automated up to Autonomous Train Operation techniques which form significant leaps in railway systems, ranging from the automation of (parts of) train operation to fully autonomous train operation.

The concepts we identified are ATO GoA2, ATO GoA4, C-DAS, TMS, ETCS HTD, ETCS Moving Block, NG Brake, DAC, Remote Train Operation and FRMCS. Not all concepts make sense to simulate in a capacity simulation yet due to negligible effects on capacity or lack of technical maturity. As a result, the concepts that we generate specific interface matrix versions for in this deliverable are C-DAS, ATO GoA2, ATO GoA4, TMS, ETCS HTD, NG Brake and DAC. These concepts will be elaborated upon in the following subsections before introducing their interface matrices respectively.

Notably, while (advanced) TMS, DAC and FDFT (Full Digital Freight Train) have a capacity effect, mainline capacity simulation cannot (yet) estimate that capacity effect. Namely, the techniques are either still at a too low level of technological maturity to make reasonable timetable parameter assumptions on them, or elements of the way of working and the associated capacity benefits are outside the current scope of capacity simulation software. Nevertheless, we will take TMS, DAC and FDFT into account in this more theoretical chapter, offering qualitative insights on where its capacity effects occur, and how these may translate into operational benefits.

Note that DAC with FDFT is a prerequisite for being able to run freight trains on railway infrastructure equipped with ETCS Moving Block, as it is necessary to ensure the required train integrity status and provide information on the train's length. Note also that FRMCS is a prerequisite for many more advanced technologies such as ATO. Such system dependencies and associated migration questions are outside the scope of this Work Package and deferred to future research.

The rest of this chapter discusses the DATO concepts and their interface matrices. Section 4.1 discusses ETCS HTD. Section 4.2 C-DAS discusses C-DAS. Afterwards, Section 4.3 discusses ATO (GoA2 and GoA4). TMS follows in section 4.4 and NG Brake in section 4.5. Section 4.6 contains a discussion on DAC/FDFT. Finally, Section 4.7 draws conclusions from the DATO-specific interface matrices.

4.1 ETCS HTD

ETCS HTD (Hybrid Train Detection, was previously known as Hybrid Level 3, HL3) is in principle an ETCS level 2 fixed block layout with additional virtual blocks. The virtual blocks are not monitored by trackside detection. The clearing of the virtual blocks is only possible by trains that have a train integrity module that ensures that the train is in one piece. The level 2 blocks have train detection systems where the physical detection systems will cover at least safety-critical locations such as switches, level crossings, station platform ends, movable bridges, and catenary overlap zones. While a regular spacing may still be needed to ensure a desired headway behind trains that are not equipped with a train integrity module, the technique in theory allows the removal of all non-critical physical train detection systems. It also allows for the specification of many new (virtual) blocks. Figure 22 below shows a schematic that explains block occupation under ETCS HTD conditions.

Within HTD-equipped trains, the train integrity module continuously communicates to the Radio Block Centre (RBC) where the rear end of the train is located. One can specify new virtual signal marker boards and accompanying shorter blocks to achieve reductions in headways. Then, for the trains running on such an HTD corridor that are running behind an HTD train, their headway to the preceding train decreases, and they can approach it more closely. In this case, capacity is increased without increasing the number of physical assets along the track. We refer to FP2-WP37 for more information on HTD, particularly its Deliverables 37.2 (Aoun et al., 2026a) and 37.4 (Aoun et al., 2026b).

In conclusion, HTD affects headway, and this is the only thing that it affects in terms of capacity building blocks. Accordingly, Figure 21 below shows the interface matrix specifically for HTD. It shows that HTD influences the capacity indicators of the number of trains per unit of time and operational stability. All intermediate steps are linked and, therefore, all business impacts can appear. We identified that the endogenous effects of comfort, safety, and wear per train are not affected in the interface matrix by HTD, as HTD does not influence them directly in addition to the capacity-induced effect.

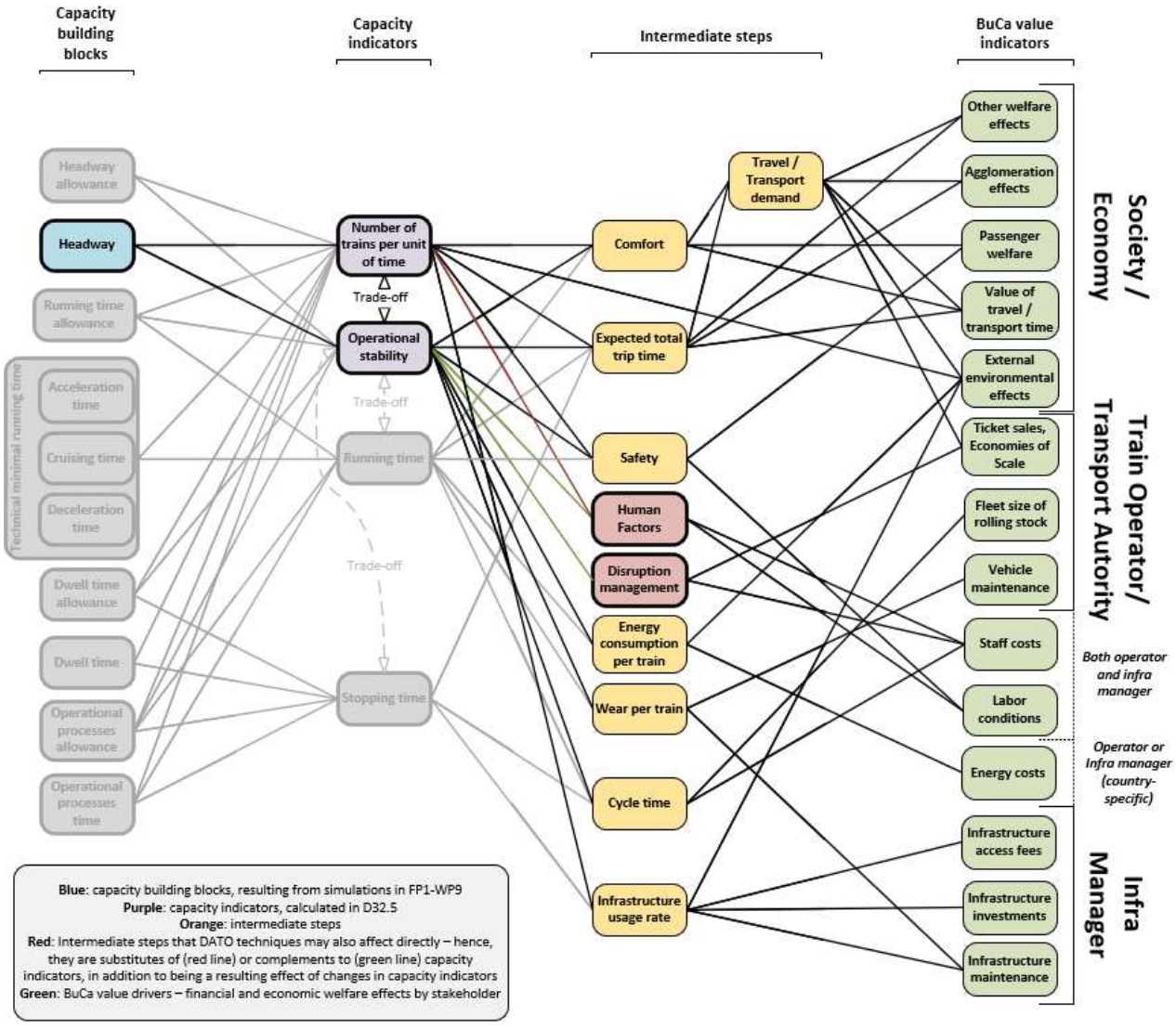


Figure 21: Interface Matrix for ETCS-HTD

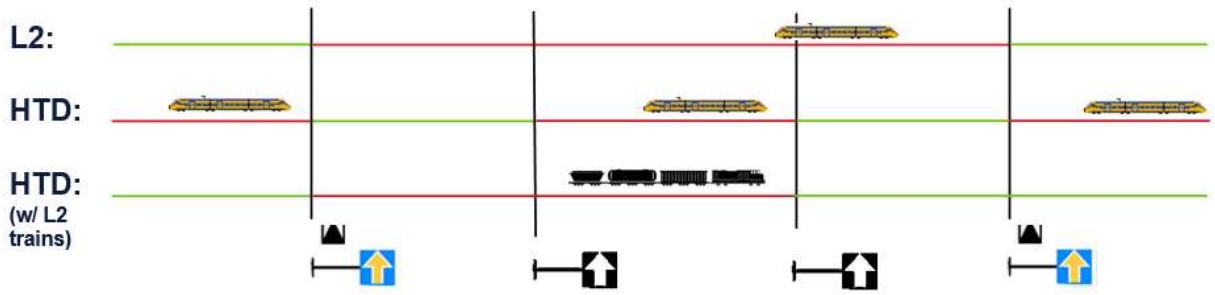


Figure 22: ETCS Level 2 vs Hybrid Train Detection: effect of shorter virtual blocks

4.2 C-DAS

C-DAS (Connected Driver Advisory System) is a driver advisory system with a communication link to external traffic control systems in each controlled area in which the train operates. This enables the provision of schedule, routing, and speed-advisory updates to trains in near real time. It also enables receipt of information from trains to these systems to improve regulation decisions. A C-DAS system can also supply a relatively energy-efficient driving strategy advice, though not the energy-optimal strategy, as Appendix A explains.

C-DAS consists of two main systems: the Trackside (TS) system and the Onboard (OB) system. These systems work together to provide real-time information and advisory recommendations to train drivers. The OB subsystem of a C-DAS may be installed on the train itself, (e.g., via a display and software hosted on the train), or it can simply be a stand-alone device (e.g., a tablet). It receives the recommendations generated by the TS system and provides them to the train driver in near real-time, displaying the recommendations on the driver's interface, typically through visual displays or audio alerts. The OB system may also collect onboard data, such as train performance metrics and geographical position, and transmit these back to the TS system for further analysis.

The system depends on train drivers following the output from the C-DAS. In addition, a C-DAS system requires a rather stable mobile network communication along the line.

The C-DAS system will decrease the deviation from the planned timetable. This will lead to less deviation in running times. Therefore, the running time allowance can be decreased. However, this depends on train driver utilization rate and the accuracy of the driver to follow all the advice of the C-DAS.

Figure 23 below shows the interface matrix for specifically C-DAS. Following the above, C-DAS potentially influences only the headway allowance and running time allowance. Nonetheless, links occur with all intermediate steps and therefore all business impacts. We identified that the endogenous effects of comfort, safety, and wear per train are not affected in the interface matrix by C-DAS, as C-DAS does not influence them directly in addition to the capacity-related effect.

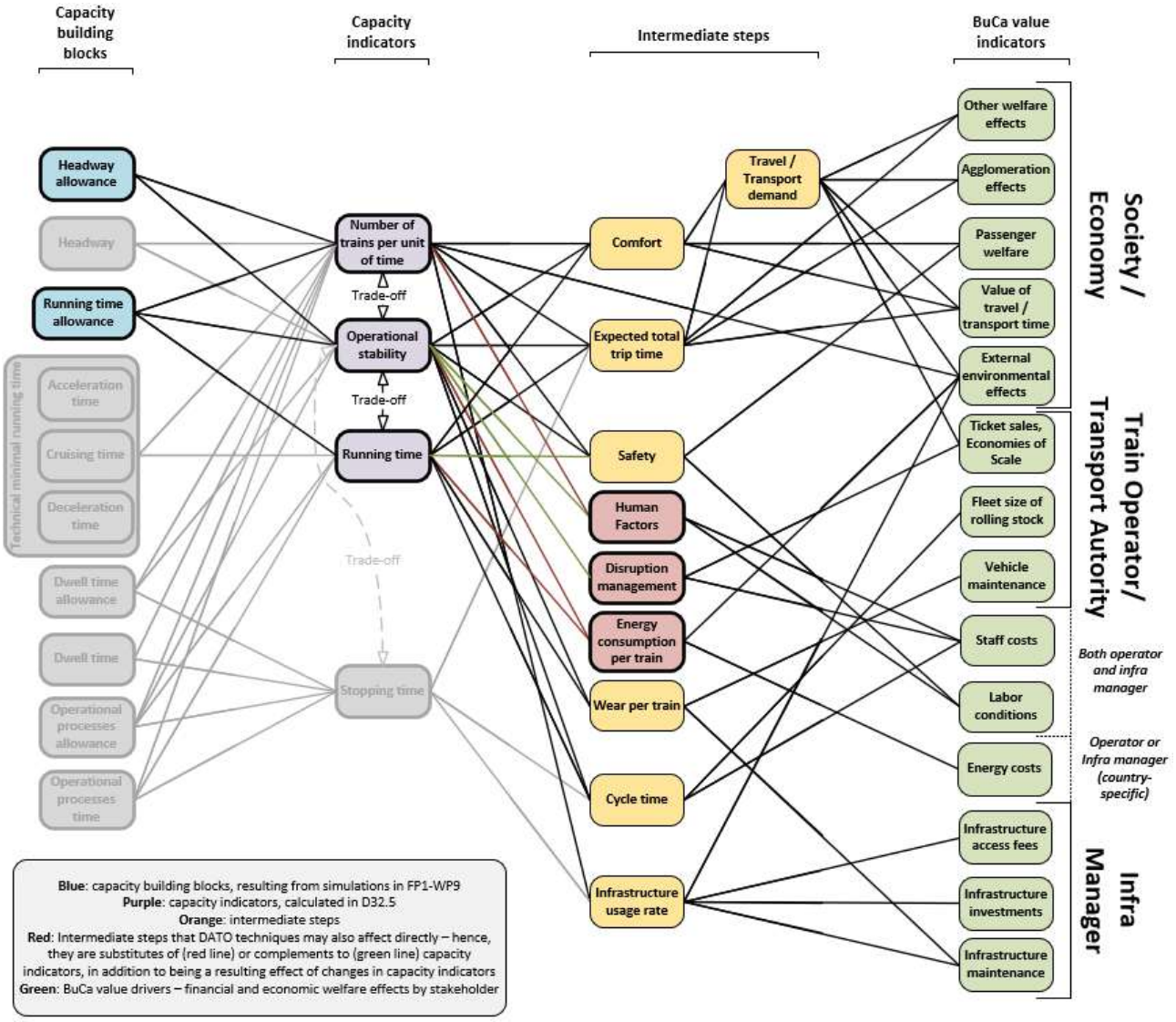


Figure 23: Interface Matrix for C-DAS

4.3 ATO

The term "ATO" stands for Automatic Train Operation, which is an overarching concept. There are four different levels of automation referred to as GoA levels (Grades of Automation) defined in the international standard IEC 62290-1:

1. GoA1: The train driver operates the train manually, possibly with the assistance of driving advisory systems.
2. GoA2: Acceleration, cruising, deceleration, and stopping are automated. The train driver remains responsible, monitors the ATO system, and intervenes if necessary.
3. GoA3: The ATO system operates the train independently. The train driver/train attendant does not need to be in the cab and can perform other tasks.

4. GoA4: The ATO system operates the train independently and intervenes in case of (potential) incidents. No train driver is present on the train. Disruptions are managed through remote control and/or by a maintenance team.

Table 5 below illustrates these GoA levels.

Grade of Automation		Door closure	Setting train in motion	Stopping train	Degraded operation in case of disruption	Energy-efficient driving
GoA1	Non-automated train operation	Driver	Driver	Driver	Driver	Maximum Coasting
GoA 2	Semi-automated train operation	Driver	Automatic	Automatic	Driver	Energy-Efficient Train Control
GoA 3	Driverless train operation	Attendant	Automatic	Automatic	Attendant	Energy-Efficient Train Control
GoA 4	Unattended train operation	Automatic	Automatic	Automatic	Automatic	Energy-Efficient Train Control

Table 5: ATO grades of automation

4.3.1 ATO GoA2

ATO GoA2 consists of two systems: ATO trackside and ATO onboard. ATO trackside serves as a proverbial mailbox. It constructs a journey profile and segment profile based on the train's status, timing points, and the timetable and route planning from the TMS. The ATO trackside may potentially also add or refine timing points and detect conflicts on its own.

This constructed plan is then delivered to the ATO system on the train. ATO onboard influences the train's traction and braking. This system considers various factors such as the timetable, infrastructure characteristics, train characteristics, safety limits, comfort limits, current time, speed, and train position. It uses this information to determine the desired speed profile, translating it into brake/acceleration/coasting commands for the train.

The general expectation is that ATO may allow faster deceleration than manual driving given the same set of context-dependent optimization criteria (such as safety, capacity, energy efficiency, and comfort). Hence, ATO affects the capacity building blocks running time and headway. It allows trains to be planned faster from origin to destination due to higher planned braking rates, and it allows trains to be planned closer together because the braking distance towards the start of the next block decreases.

In addition, ATO allows a reduction in running time allowance and headway allowance. The variance of running times will decrease as the ATO onboard removes the need for driver allowance if drivers engage the ATO GoA2 system most of the time. Moreover, tests suggest that ATO algorithms may be able to run close to the technical minimal running time, close or equal to the best performing drivers from a capacity maximization perspective.

Since a train will stop on almost the same position every time and the departure process might be more efficient, a shorter dwell time or dwell time allowance might be considered. So far, this effect has not been proven or observed for ATO GoA2.

Figure 24 below captures the above information. It shows that ATO GoA2 influences all capacity indicators except for stopping times. All intermediate steps are linked and therefore all BuCa value indicators may be impacted. Since ATO may have a direct effect on comfort, safety, human factors (see D32.4, Lo et al., 2026), energy consumption per train (see Appendix A) and wear per train (see D32.3, Hé et al., 2025), we leave those intermediate steps as potentially endogenous. However, disruption management is not endogenous, as there is no direct effect of ATO on the level of disruption management activities if the ATO trackside does not carry out traffic management tasks automatically.

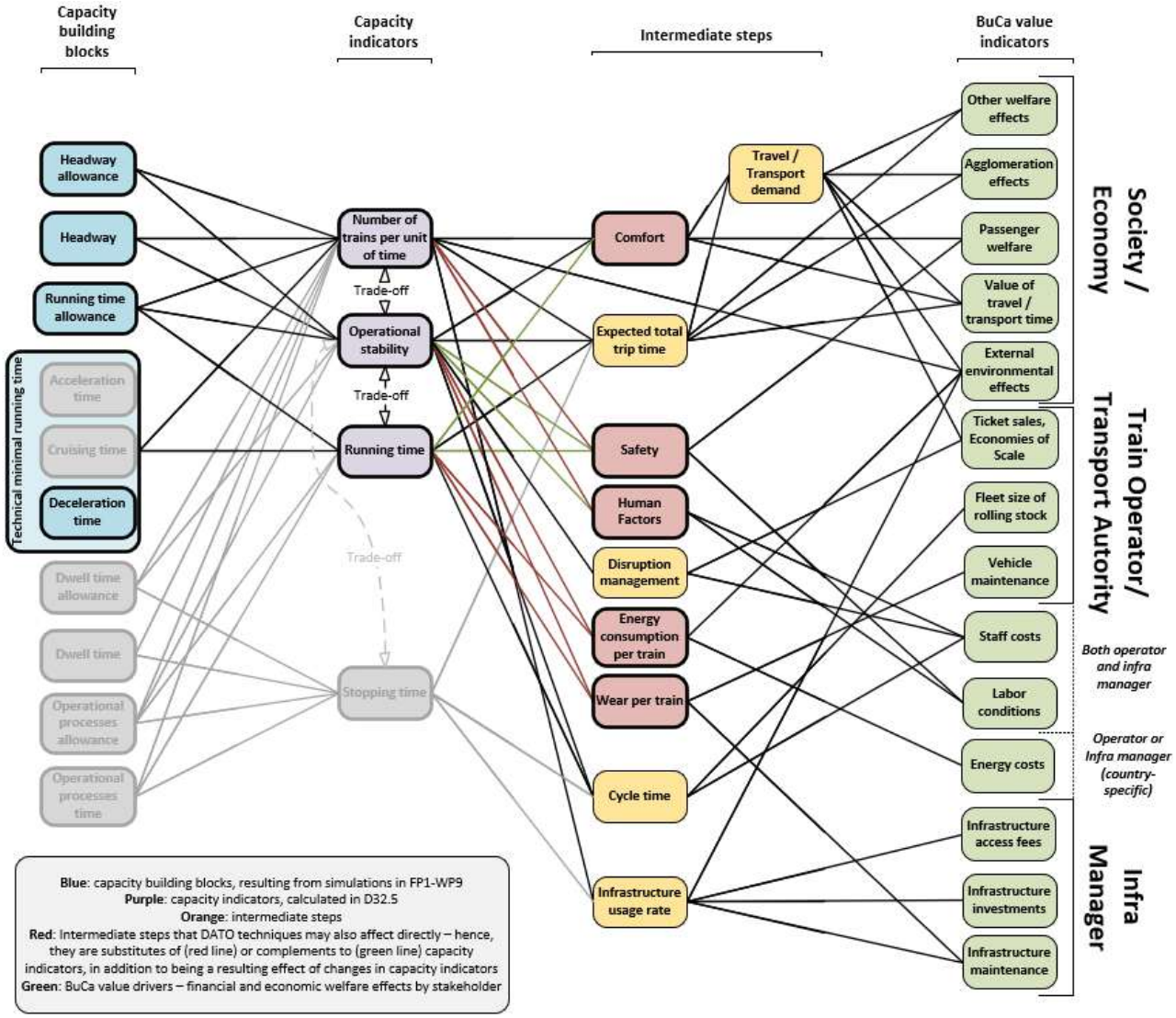


Figure 24: Interface Matrix for ATO GoA2

4.3.2 ATO GoA4

In contrast to ATO GoA2, ATO GoA4 operates without a train driver present in the train cab and no drive-capable personnel on board the train. The most significant difference is that ATO GoA4 must fulfil additional functions, requiring the incorporation of extra systems. These functions include monitoring and responding to hazards on and around the track. Specifically, ATO GoA4 requires an obstacle detection system comprising sensors on the train (such as camera or lidar) and an image recognition model to detect and respond to obstacles. In the event of disrupted situations, the first step is to see if the system can handle them autonomously as a second step mobile maintenance teams or remote-control centres would manage the situation. Since the latter would be time- and resource-intensive, trains running with GoA4 require a high degree of reliability in the on-board systems.

For ATO GoA4, all building blocks affected for GoA2 are still present for the same reasons as previously mentioned for GoA2. In addition, the boarding and alighting process may be shorter due to complete elimination of human check and reaction times. Therefore, the dwell time allowance may be decreased. Also, with GoA4, some operational processes and their allowance can be shortened, such as elimination of the operational process of driver walks between cabins or at the yard. Therefore, ATO GoA4 may decrease turnaround or shunting and stabling times can be decreased. Finally, ATO GoA4 may allow for a higher braking rate due to the inability of human drivers to still intervene if they get anxious about overshooting a platform or signal.

Figure 25 below shows the according ATO GoA4 interface matrix. Notably, almost all capacity building blocks may be affected, and all intermediate steps we identified as potentially endogenous for one or more DATO techniques, are indeed potentially endogenous for ATO GoA4. This shows that ATO GoA4 is a major change in the railway system.

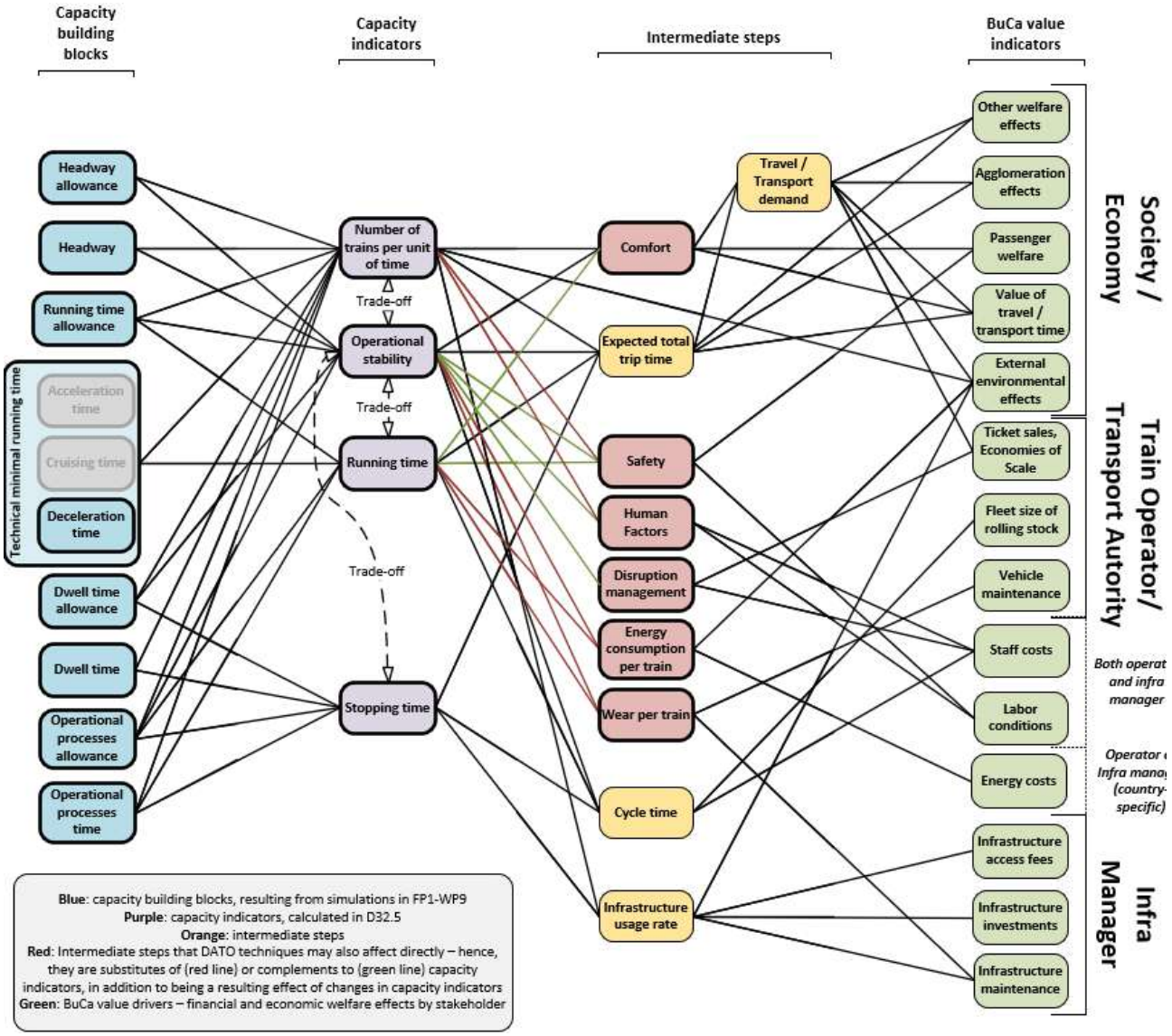


Figure 25: Interface Matrix for ATO GoA4

4.4 TMS

TMS (Traffic Management System) is the global system for monitoring and controlling the traffic by means of remote control of the signalling systems from the control centres. It covers a broad range of functionalities. Traffic management systems can include functionality to handle location and speed information from C-DAS and ATO fitted trains in the managed area. This information from C-DAS/ATO is useful to update the real time traffic plan (RTTP), allowing a better accuracy in the real time conflict detection. C-DAS traditionally provides position information from a GNSS-system, whereas ATO in a ETCS environment provides position information by means of data transfers to the RBC.

A main task of a railway TMS is to provide information about routes and times to trains for automized conflict-free or conflict-resolving train operation. The RTTP provided by TMS will be supplied to the ATO-TS or the driver with C-DAS. Especially ATO trains can be managed and predicted to be on a

location on a specific time. Therefore, less conflicts between trains will occur and less headway allowance will be needed.

A TMS might also deliver a RTTP that includes optimized travel times based on environmental impacts on the running time, such as weather or temporary speed restrictions. The ATO or drivers can then become aware of such conditions ex ante. As this allows preventative anticipation strategies, less running time allowance may suffice to achieve the same operational stability.

Figure 26 below shows the according TMS interface matrix. It shows that TMS has the potential to influence all capacity indicators except stopping times. All intermediate steps are linked and, therefore, all BuCa value indicators may be impacted. Since TMS may have a direct effect on human factors, disruption management efforts, and energy consumption per train, we leave those intermediate steps as potentially endogenous.

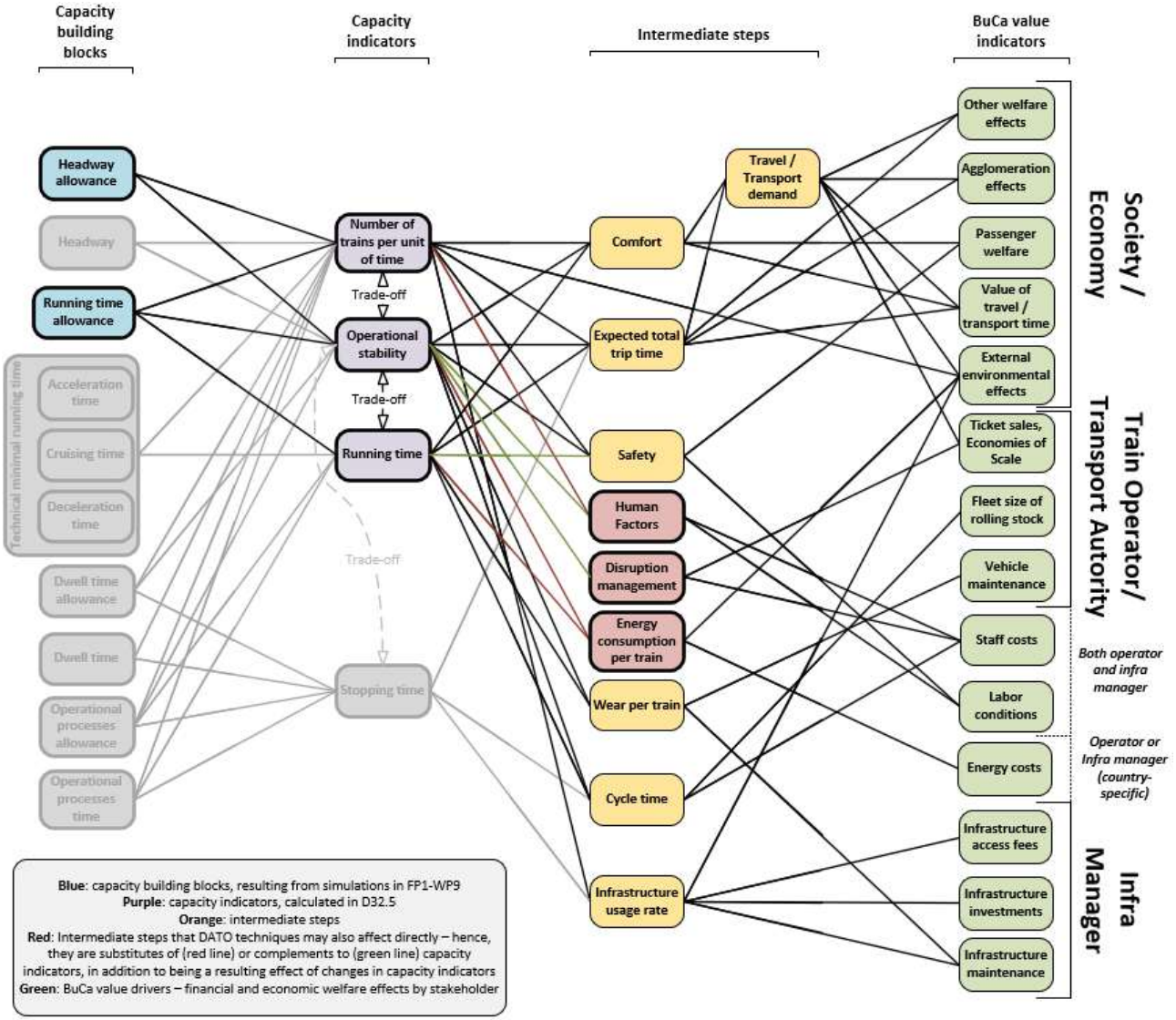


Figure 26: Interface Matrix for TMS

4.5 NG BRAKE

The work on Next Generation (NG) brake systems in R2DATO (WP17 and WP18) concerns a Brake and Adhesion Management System (BAMS) and Adhesion Determination Systems (ADS). In the context of capacity, this system will determine the current adhesion or also receive the predicted adhesion further on the line from other trains equipped with BAMS and ADS. Based on this information, NG Brake will determine the maximum available deceleration and supply this information to the ETCS unit and/or available adhesion information to the ATO onboard unit. This will activate adhesion-related functions such as sanding units when the track is too slippery and improve the adhesion usage or increase the available adhesion resulting in higher deceleration values. In addition, NG Brake will be able to mitigate underperformance of the brakes on individual axles by correcting for this with the applied braking force on the other axles.

As a result, planned assumed deceleration rates as well as ETCS supervised braking decelerations may become higher, subject to constraints from comfort and human factors.

This will decrease technical minimal running times as well as the headway between trains. In addition, under conditions with reduced adhesion, the actual braking distance of trains with BAMS is closer to what is technically achievable under dry conditions. This means that less running time allowance is needed to compensate for weather variance.

Since the adhesion parameters are known on the parts where trains brake or accelerate, running times can be calculated more accurately during periods with reduced adhesion. The TMS can adjust the RTTP given on these circumstances and/or the ATO onboard can adjust the driving strategy based on the more accurate description of the track condition and prevent or decrease delays.

Figure 27 below shows the according NG Brake interface matrix. It shows that NG Brake influences all capacity indicators except for stopping times. Nevertheless, all intermediate steps are linked and, therefore, all BuCa value indicators may be impacted. Since NG Brake may, in addition to a capacity-induced effect, also have a direct effect on comfort (higher ATO deceleration), safety (less overshooting potential), human factors (drivers have to trust the system when it brakes late), and wear per train (less wheel slides and overheating of brake pads), we signal these intermediate steps as potentially endogenous.

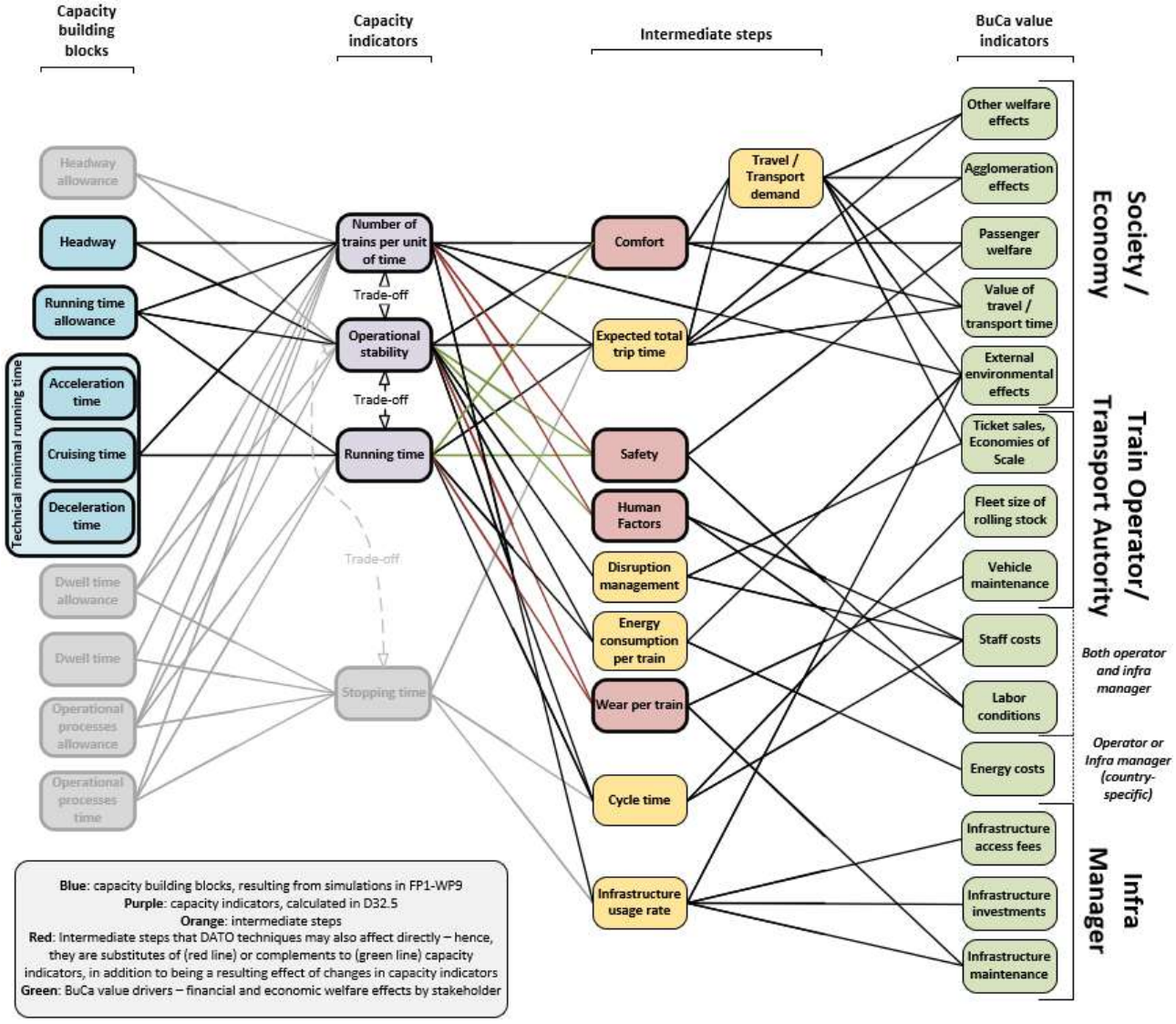


Figure 27: Interface Matrix for NG Brake

4.6 DAC FOR FREIGHT RAIL TRANSPORT AND FULL DIGITAL FREIGHT TRAIN

Nowadays, screw couplers still form the coupling standard for freight trains in European countries. With screw couplers, workers must climb between wagons to hook and un-hook them, requiring physically exhausting manual operation in a hazardous environment. Digital Automatic Coupling (DAC) is an innovative solution to automatically couple and decouple freight wagons both physically (the mechanical connection and the air line for braking) as well as digitally (electrical power and data connection).

DAC may increase in efficiency and transparency of rail freight (Shift2Rail, 2021). It is a prerequisite for automated yard operations such as automatic shunting, which could make freight by rail more competitive. In addition, DAC enables the Full Digital Freight Train (FDFT) concept, which allows freight trains to use the ETCS Gamma braking model, potentially also allowing freight trains to use virtual blocks under ETCS HTD or even ETCS Moving Block. FDFT can be equipped with electronic pneumatic brakes or better, which will enable higher deceleration rates for freight trains.

Per the above, DAC and FDFT will reduce the operational process time and associated allowances. In addition, improved deceleration rates will shorten headways and running times. Figure 28 below shows the according DAC and FDFT interface matrix. It shows that DAC impacts all capacity indicators, all intermediate steps, and all BuCa value indicators except for passenger welfare as this is a freight technology. DAC/FDFT may, in addition to a capacity-induced effect, also have a direct effect on safety (safer coupling), human factors (better working conditions due to removal of manual coupling, but also changed operational roles on the yard and for the train drivers), disruption management (improved re-processing of delayed freight), energy consumption (longer trains will decrease the energy consumption per transported weight) and wear per train (harder braking). Hence, we signal these intermediate steps as potentially endogenous.

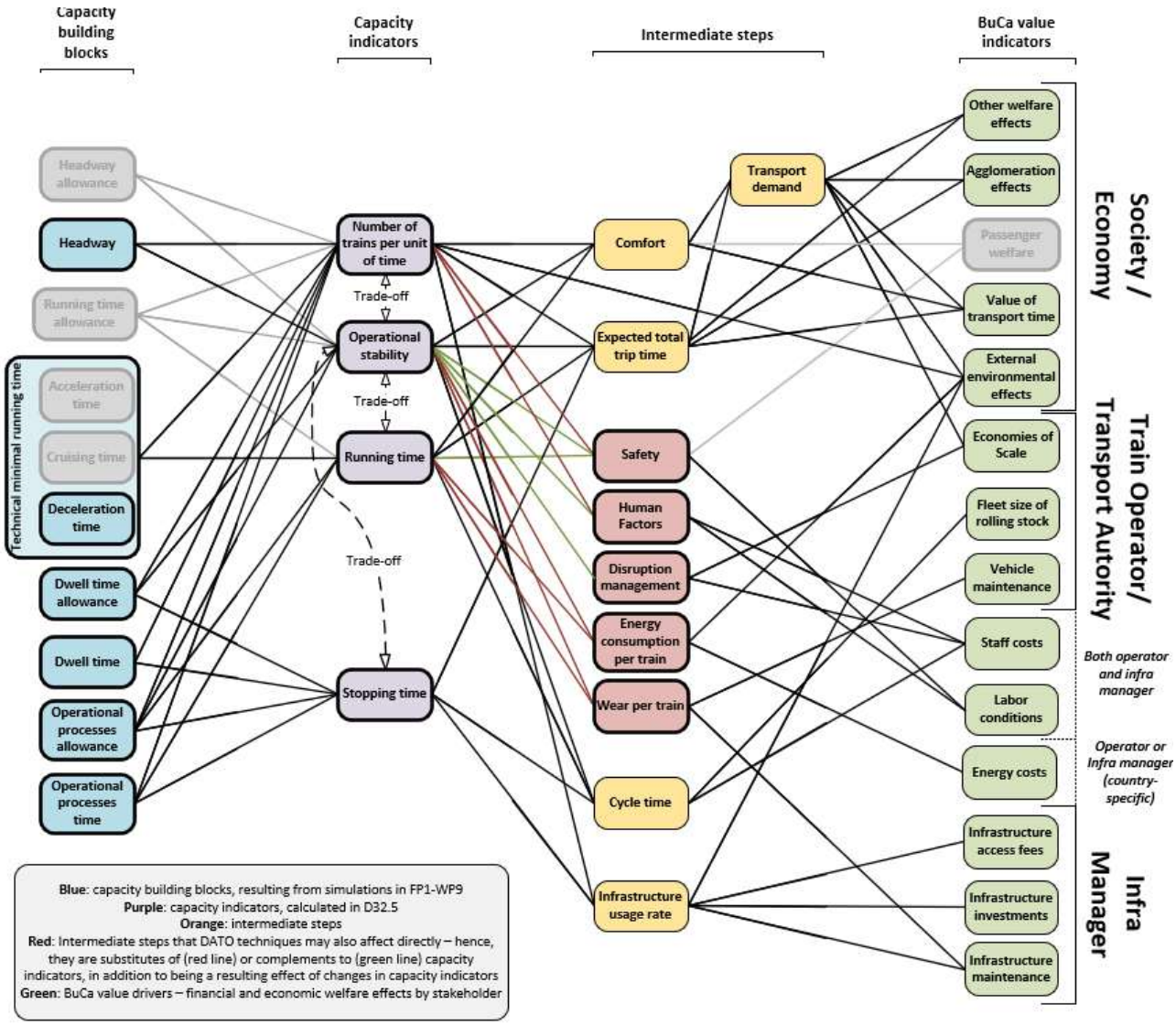


Figure 28: Interface Matrix for DAC and FDFT

4.7 Overview of Interface Matrices and DATO techniques

We summarize how the DATO techniques affect different capacity building blocks in Table 6 below. Notably, ETCS-HTD only affects headway, ATO GoA4 has the largest transformation impact as it impacts every single capacity building block, and the running time allowance is affected by the highest number of DATO techniques.

Another conclusion is that the spatio-temporal behaviour of trains is so interlinked that despite most techniques only affecting a subset of capacity building blocks, all intermediate steps are impacted by all DATO techniques considered.

For more detailed discussion on how DATO techniques influence capacity building blocks, with a focus on how to model them in microscopic capacity simulations, we refer to FP1-D8.3 (Pot et al., 2025) and FP1-D9.2 (still to be submitted).

Relation matrix	ETCS-HTD	C-DAS	ATO-GoA2	ATO-GoA4	TMS	NG-Brake	DAC/ FDFT*
Headway allowance		X	X	X	X		
Headway	X		X	X		X	X
Running time allowance		X	X	X	X	X	X
Technical minimum Running time							
-> Cruising time							
-> Acceleration time							
-> Deceleration time			X	X		X	X
Dwell time allowance				X			X
Dwell time				X			X
Operational processes allowance				X			X
Operational processes				X			X

Table 6 - Relations between Capacity Building Blocks and DATO concepts

** Freight trains only*

5 APPLICATION - SIMULATION SCENARIOS

To demonstrate the economic effects of selective DATO techniques, this and the following chapters describe and process DATO capacity simulation output towards economic and financial effects, guided by the interface matrices developed in previous chapters.

Specifically, we use microscopic capacity models and simulations developed as part of FP1-WP8+9 (see Pot et al., 2025), which were directly modelled by two authors of this Deliverable (specifically, Emil Jansson for the Swedish models, Thomas van den Berg for the Dutch models). In such, we guarantee model validity and correct interpretation of results, as well as getting direct access to the raw data for our BuCa analysis.

The goal of the exercise is to give an initial idea of the scope and size of capacity effects and resulting economic and financial effects for the DATO techniques ATO GoA2, ATO GoA4, HTD, and NG Brake, across a diverse range of logistical and geographical contexts.

Chapter 5 presents the capacity simulation scenarios we analysed. First, Section 5.1 presents a generic overview of the scenarios. Next, Sections 5.2 (NL) and 5.3 (SE) describe the respective infrastructure and timetable characteristics, the modelling assumptions and technical parameters used to approximate the effects of DATO on the spatio-temporal behaviour of trains, and the measurement methods for capacity indicators, which correspond to the approaches outlined in Chapter 3.

5.1 OVERVIEW SCENARIOS

The microscopic railway models and simulations were made in FP1 WP9 with different DATO concepts and different types of lines and traffic in different countries. Deliverable 8.3 (Pot et al., 2025) first described these. Table 7 below presents an overview of the simulated scenarios from WP9 that we will use as input for this Deliverable. When a DATO concept is already considered as an existing practice, it forms the reference, or null scenario.

Model	Simulation software	ETCS L2	C-DAS	ATO GoA2	ATO GoA4	NG Brake	HTD	Traffic type
(NL) SAAL	RailSys	(=Ref)	(=Ref)	X	X	X (on ATO GoA2)	X	Dense mixed, dense passenger
(SE) Stockholm	RailSys	(=Ref)		X				Dense passenger
(SE) Malmö	RailSys	(=Ref)		X				Dense passenger
(SE) Norrköping-Mjölby	RailSys	(=Ref)		X				Mixed mainline
(SE) Stockholm-Linköping	Railsys	(=Ref)				X		High speed

Table 7: Simulation models from FP1-WP9 analysed here, by software tool, DATO concepts tested, and traffic type

Before describing the simulated cases in more detail, we first give the following contextual note. To keep the scope of the calculation towards BuCa value indicators manageable, we only take one scenario variant for each DATO concept into account, in which the 100% of the modelled (passenger for HTD and NG Brake) trains use the DATO concept. We also limit the number of infrastructure and train parameter variants compared to the number of variants analysed within FP1-WP9. For a full overview that goes into further detail regarding infrastructure variants and timetable variants, we refer to the associated Deliverable there (FP1-D9.2; still to be published).

5.2 DESCRIPTION OF GEOGRAPHY, TRAFFIC, AND MODEL PARAMETERS (NETHERLANDS)

The SAAL-corridor (Schiphol airport – Amsterdam Zuid – Almere – Lelystad) is one of the busiest railway lines in the Netherlands, situated around the city of Amsterdam with a line length of roughly 60 kilometres. The line is to be equipped with ETCS Level 2 as part of the “ESAAL” project, which does not exactly match the SAAL corridor as it gets cut off beyond Schiphol airport, before Lelystad, and includes some branches. Figure 29 below shows the extent of this ETCS roll-out project, red indicating the core and orange indicating branches that will too be upgraded to ETCS Level 2.



Figure 29: (E)SAAL corridor (NL) use case map

The infrastructure consists of two sections with four parallel tracks. Figure 30 below presents a schematic overview of the entire corridor. Traffic on the line is dense and contains a mix of stopping and intercity services as well as freight trains from Venserpolder junction (Vspa) to Hilversum (Hvs). The number of trains on the SAAL-corridor ranges from 8 to 18 trains per track per direction per hour, using a future timetable that was designed to meet current demand, and that the “ESAAL” projected infrastructure can barely run a stable timetable on. For the latter reason, capacity upgrades through DATO technique implementations may be especially interesting.

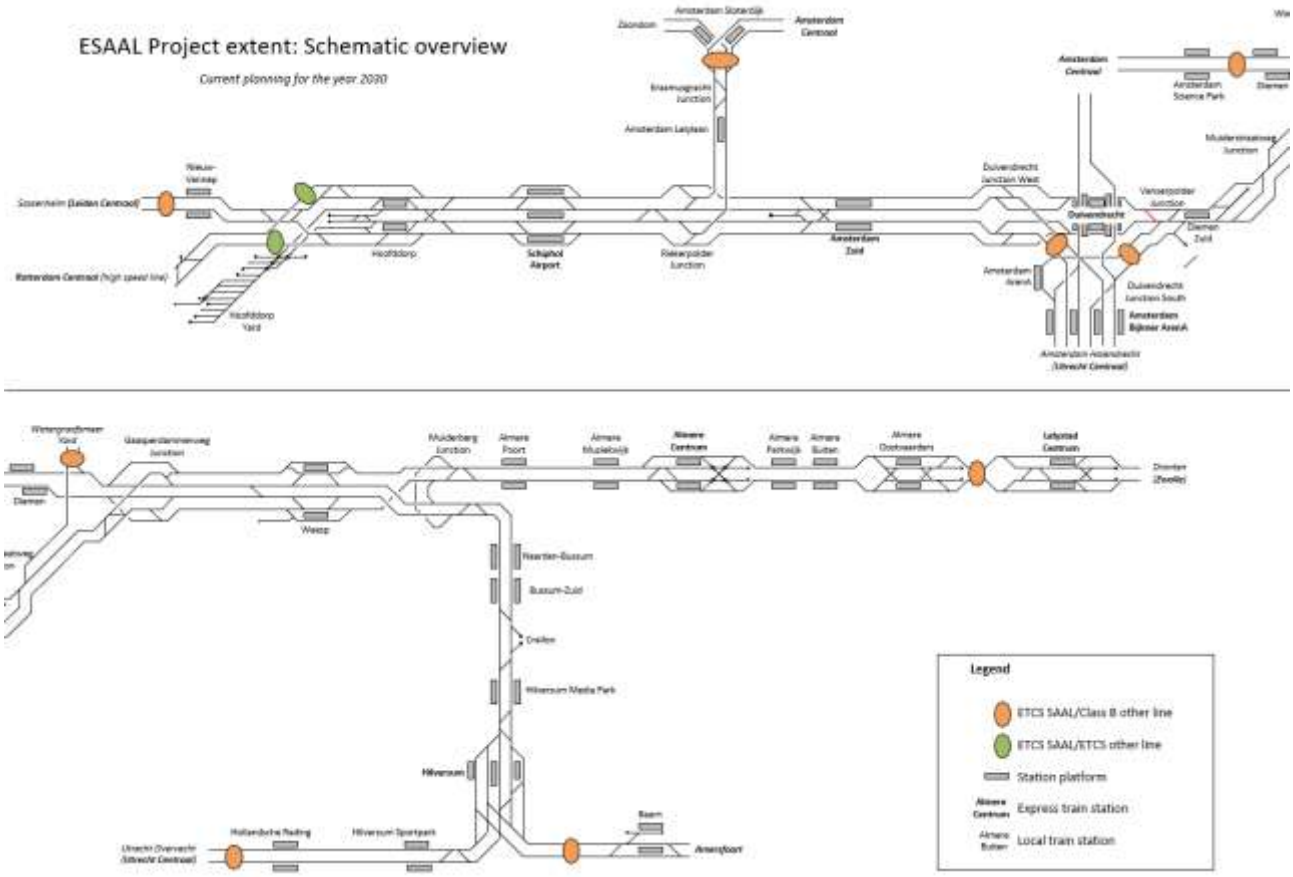


Figure 30: Schematic overview of (E)SAAL Corridor: Stations, tracks, transitions

Table 8 below shows the timetable and simulation parameters we assume for the DATO concepts ATO GoA2, ATO GoA4, and NG Brake. The parameters ensure that spatio-temporal behavioural changes in modelled trains follow the effect we expect DATO concepts to have. We set our parameters after thorough consultation with capacity and DATO experts, including those at the largest passenger train operator (NS).

5.2.1 Braking rates

Realised braking rates depend on whether the braking action is bounded by an ETCS braking curve or not. If the driver brakes freely, without being bounded by an ETCS braking curve, then we assume they follow a constant deceleration of -0.5 m/s^2 for passenger trains and -0.2 m/s^2 for freight trains. While some train drivers may consistently be able to brake faster, the given values approach decades of real-life data of the average driver in the Netherlands within a context of achieving some combination of capacity, safety, and comfort. Given the same set of context-dependent optimization criteria, we assume that the ATO will be able to consistently brake faster based on expert insight and as result of an early real-life test. Specifically, we assume ATO GoA2 passenger trains have a free braking rate of -0.72 m/s^2, noting that this likely errs on the safe or low side.

By contrast, when braking towards an end of movement authority, the train eventually becomes bound by the ETCS permitted curve. We assume based on driver tests that train drivers still follow a braking rate of -0.5 m/s^2 (passenger) or -0.2 m/s^2 before intercepting the permitted curve at lower speed, and that they then follow the ETCS permitted curve until the release speed before stopping.

Parameter	Reference (ETCS L2)	ATO (GoA2)	ATO (GoA4)	NG Brake & ATO (GoA2)
Free braking rate for passenger trains, and adhesion condition	-0.5 m/s² Dry -0.33 m/s² Low -0.20 m/s² Very low	-0.72 m/s² Dry	-0.72 m/s² Dry	-0.93 m/s² Dry -0.93 m/s² Low max -0.72 m/s² Low intm -0.4 m/s² Very low
Free braking freight trains	-0.2 m/s²	-0.3 m/s²	-0.3 m/s²	-0.3 m/s²
Driver reaction	2 s	0 s	0 s	0 s
T_driver	4 s	4 s	2s	4 s
Kdry_rst	ref	ref	ref	(1 + ref) / 2 intm 1 max
Kwet_rst	ref	ref	ref	(1 + ref) / 2 intm 1 max
Standard running time allowance	7% IC 6% Stopping 0% Freight	4% IC 4% Stopping 0% Freight	4% IC 4% Stopping 0% Freight	4% IC 4% Stopping 0% Freight
Headway allowance	60 s IC 45 s Stopping	45 s IC 30 s Stopping	45 s IC 30 s Stopping	45 s IC 30 s Stopping
Minimal stopping time passenger trains	ref	ref	-10 s IC - 4 s Stopping	ref

Table 8: SAAL (NL) study parameters for ATO and NG Brake

The braking rates of the ETCS permitted curve, which the train will follow if it hits an end of movement authority, depend on parameters that are specific to the rolling stock. Parameters that may change because of ATO or NG Brake are T_driver, Kdry_rst, and Kwet_rst (ERA, 2020).

First, T_driver is the parameter that defines the time distance from the emergency intervention curve to the permitted curve. Hence, lower values for T_driver shift the braking curve closer to the last possible safe moment to brake, running time and headway benefits. For drivers, the current value is set at 4 seconds. We assume that with ATO GoA2, drivers will get too uncomfortable and still intervene even if T_driver is decreased, such that no capacity benefit will be present. However, with ATO GoA4, no drivers will be present anymore, and so trains will be able to run closer to the intervention curve. Accordingly, we assume that T_driver decreases from 4 to 2 seconds for ATO GoA4.

Second, Kdry_rst and Kwet_rst are speed-dependent safety-induced correction factors on the nominal braking rates for dry and low adhesion conditions. If their value is 1, then the nominal braking rates do not get adjusted. If their value is below 1, the nominal braking rates are downsized

proportionally. We assume that Kdry_rst and Kwet_rst will improve for the variants of NG Brake that we calculate effects for in this document. We base this on consultation with experts from the technical NG Brake work packages (WP 17+18) within FP2. They proposed both a realistic 'intermediate' version of their technique including ETCS integration, as well as a 'maximized' version of their technique including ETCS integration, which would require maximal investment. In the maximized version, Kdry_rst and Kwet_rst both improve to a value of 1, and there is no imposed penalty on the nominal braking rates anymore. In the intermediate version, we assume an improvement of half the gap between 1 and the reference Kdry_rst and Kwet_rst.

A final parameter we assume changes for ATO is the driver reaction time. This represents the reaction time to an upgraded signal aspect or movement authority if a train was previously braking towards it or standing still. Hence, the driver reaction time only occurs in simulations with delayed trains. For the scenarios with manual driving, we assume a reaction time of 2 seconds, while we assume no reaction time for ATO. This assumption is based on the ATO getting the information directly, while the train driver has the risk of looking at other things and might take a few seconds to see the updated signalling message.

For NG Brake, we model several track adhesions. Dry conditions are normal track conditions which represent an adhesion factor (μ) of at least 0.15. Low adhesion conditions are track conditions with a water-soap condition, representing an adhesion factor (μ) of 0.05. Very low adhesion conditions are track conditions with oil, representing an adhesion factor (μ) 0.03. Low adhesion conditions are slightly worse than rain, while very low adhesion conditions mimic the effect of wet tree leaves on the track. In simulation, we change the braking parameters to reflect the effect of lower adhesion.

5.2.2 Running time allowance

As explained in Chapter 3, the running time allowance is a combination of (1) allowance to capture variations at the engineering level, such as differences in track condition, temporary speed restrictions, and weather, and (2) variations at the driver level in the applied travel strategy. In the Netherlands, for the reference case, we currently use a planning norm of 7% (Intercity trains), 6% (stopping trains), and 0% (freight trains). In these numbers, variation in driver behaviour accounts for 3% (Intercity trains), 2% (stopping trains), and 0% (freight trains)[1], with engineering variability accounting for the remaining percentage points. Accordingly, we assume that ATO eliminates driver variability, and that the allowance decreases by the size of the current running time allowance for driver variability.

Note that, in accordance with the software, we call this parameterized restriction on the technical minimum running time a Standard Allowance. This represents a mandatory running time allowance that the trains must follow in timetable inputs and in deterministic simulations. There may exist additional running time allowance in addition to the standard allowance if the difference in scheduled arrival and departure time exceeds the technical minimal running time including the standard allowance.

[1] We note that freight trains do have driver variation, but the planning norm is to instead get running time buffer by freight trains not running as much as their paths are scheduled and running at a lighter weight than they are planned as in simulation, hence being able to run faster than planned. We postpone a proper test of the ATO running time buffer benefits for freight trains to future research.

5.2.3 Headway allowance

Estimates by experts on driver variation suggested that a decrease of the headway allowance could be achieved by ATO for the Dutch case. For this study, we assumed the lower bound that was reported internally within ProRail, which is 15 seconds.

5.2.4 Stopping time

For ATO GoA4, we assume the minimal stopping time decreases due to faster system reactions and no involvement of a driver or attendant. Note that we assume a decrease in the minimal stopping time. Real timetabled stopping times may far exceed this, in which case the benefit would only materialize for delayed trains.

5.2.5 Timetable and infrastructure variants for HTD and NG Brake

Having described the timetable parameters that change across DATO techniques in the Dutch SAAL study, we now describe parameters that change within DATO techniques. Specifically, we report four infrastructure variants for HTD, and four timetable variants for NG Brake.

The four HTD variants are as follows. They vary block lengths and the number of remaining axle counters.

1. Removal of all non-safety-critical axle counters and keeping the virtual block lengths the same as the old physical blocks. In this case, about 70% of the blocks are turned into virtual blocks.
2. Removal of half of the axle counters by maximizing the remaining physical block length to roughly 1,000 meters, to prevent exponential capacity losses. Virtual block lengths the same as the old physical blocks. In this case, about half of the blocks are turned into virtual blocks.
3. Removal of half of the axle counters by maximizing the remaining physical block length to roughly 1,000 meters, to prevent exponential capacity losses. We divide the virtual blocks by two where possible, meaning that we conform to infrastructure restrictions on the placement of new blocks. We only implement this on the *Flevo line* part of the SAAL corridor, which lies between Weesp and Almere Oostvaarders.
4. Removal of half of the axle counters by maximizing the remaining physical block length to roughly 1,000 meters, to prevent exponential capacity losses. We divide the virtual blocks by four where possible, meaning that we conform to infrastructure restrictions on the placement of new blocks. We only implement this on the *Flevo line* part of the SAAL corridor, which lies between Weesp and Almere Oostvaarders.

5.3 Description of geography, traffic, and model parameters (Sweden)

In Sweden, four lines have been used as a case study. Table 9 below presents an overview of the four lines in terms of track length and number of trains per type.

	Stockholm Commuter Line	Malmö City Tunnel	Norrköping-Mjölby	Stockholm-Linköping (East link)
DATO concepts	ATO (GoA2)	ATO (GoA2)	ATO (GoA2)	ATO (GoA2) & NG Brakes
Length (km)	11	14	64	200
Commuter trains	538	333	96	0
Regional trains	0	188	67	92
Long-distance trains	0	0	38	46
Freight trains	0	0	19	0
Total number of trains	538	521	220	138 (334)
Number of trains per hour and direction (peak)	16	15	8	6 (13)

Table 9: Overview of characteristics for Swedish use cases

The Stockholm Commuter Line (Solna/Huvudsta - Stuvsta/Farsta strand) is a 16km/20km long double-track line for commuter trains in the centre of Stockholm and has a very dense timetable. For the valuation of time the part between Tomteboda Övre and Älvsjö is used. In the simulation, a total of 538 commuter trains were simulated for one day. ATO GoA2 could be a solution to increase the number of trains per unit of time that the line can process without building new infrastructure. The increase of capacity will be needed in the future to accommodate an increase of travellers. The line consists of four stations of which one is four-track and three are double-track. Figure 31 below maps the study area.

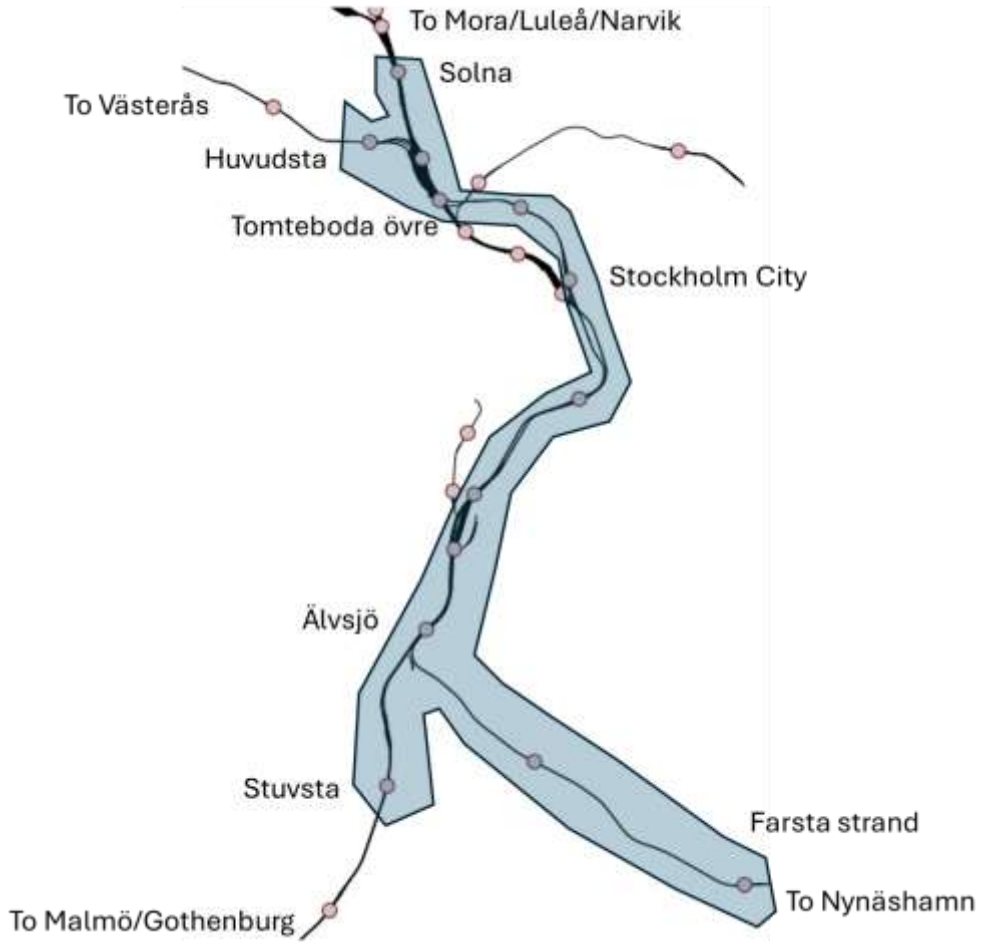


Figure 31: Stockholm Commuter Line (SE) use case map

Like the Stockholm Commuter Line, the Malmö City Tunnel (Malmö godsbangård - Lernacken/Svågertorp) is a 14 km double-track line with only passenger traffic under the city of Malmö. A total of 521 trains (333 commuter and 188 regional) were simulated for one day. The line consists of three stations of which two have four tracks and one has two tracks. The line is considered a bottleneck in the region, and more capacity will be needed. Figure 32 below maps the study area.

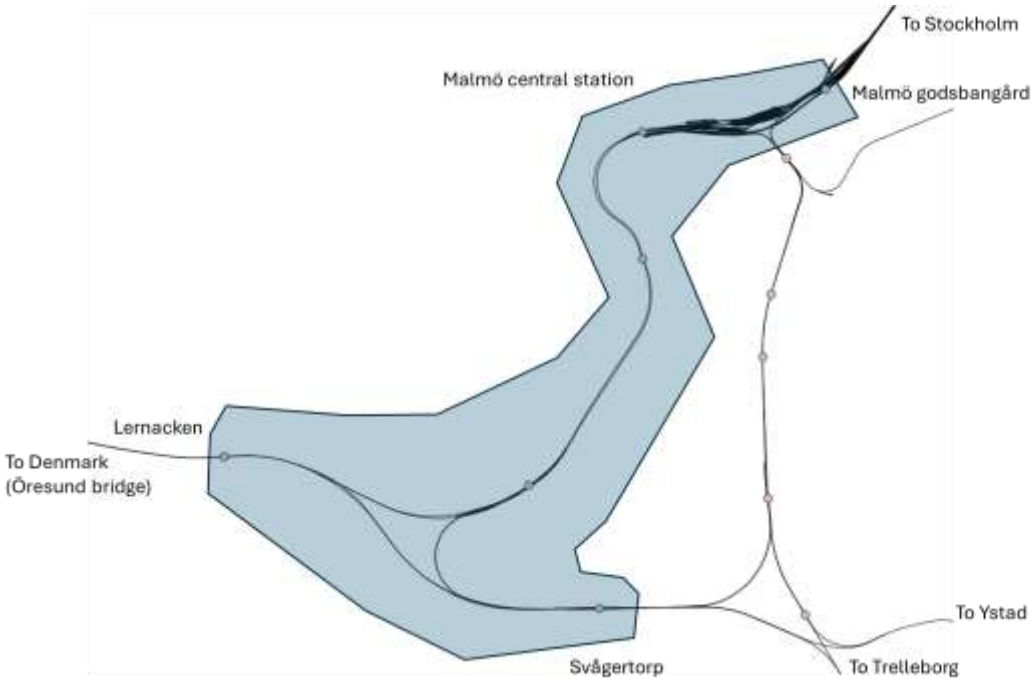


Figure 32: Malmö City Tunnel (SE) use case map

Norrköping - Mjölby (Fiskeby - Mjölby) is a 64 km long double-track part of the Southern Main Line, with mixed traffic of commuter, regional, long-distance, and freight trains. A total of 220 trains (96 commuter, 67 regional, 38 long-distance, and 19 freight) were simulated for one day. Only the passenger trains are considered in the results. There are seven stations between Norrköping and Mjölby of which five are passenger stations. Figure 33 below maps the study area.

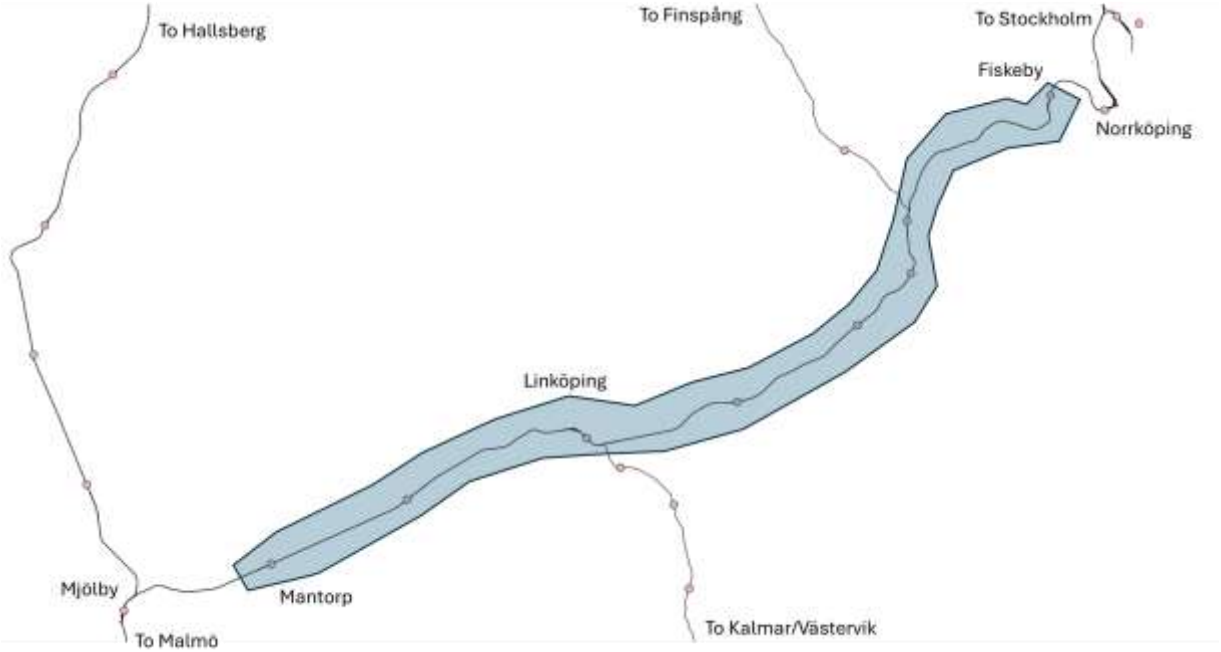


Figure 33: Norrköping-Mjölby (SE) use case map

Finally, Figure 34 below maps the East Link (Stockholm Central Station - Linköping). This is a planned double-track high speed line between Järna and Linköping. The new line will be 160 km long with a maximum speed of 250 km/h. The distance between Stockholm and Linköping is 200 km. The long-distance trains are expected to stop in Norrköping and Linköping, while the regional trains are expected to stop at Vagnhärad, Nyköping, Skavsta, Norrköping and Linköping. The line is expected to be open in 2035. A total of 138 trains (92 regional, and 46 long-distance) were simulated on the East Link and between Järna and Stockholm another 196 trains were part of the simulation that share tracks with the trains from the East Link on parts of the model. However, these 196 trains are not part of the results.



Figure 34: Stockholm-Linköping (SE) use case map

Table 10 below shows the parameters of the simulation for the DATO concepts ATO GoA2 and NG Brake. For a detailed explanation of the parameters, we refer to FP1-D9.2 (still to be published). There is an ongoing debate of what the impact of ATO (GoA2) and NG Brakes on parameters to simulate trains would be on the Swedish railway network. Together with experts from Trafikverket, we have set the following parameters for the Swedish cases.

	Reference (ETCS L2)	ATO (GoA2)	NG Brake	NG Brake & ATO (GoA2)
Free braking passenger trains[1]	-0.6 m/s^2	-0.6 m/s^2	-	-
Free braking freight trains[2]	-0.3 m/s^2	-0.3 m/s^2	-	-
Driver reaction	2 s	0 s	2 s	0 s
T_driver	4 s	2 s	4 s	2 s
Kdry_rst	Ref	Ref	0.82	0.82
Kwet_rst	Ref	Ref	Ref	Ref
Standard allowance (not allowed to be used for delay recovery)	3%	0%	3%	0%
Headway allowance	Not used	Not used	Not used	Not used
Minimal stopping time passenger trains	Ref	Ref	Ref	Ref

1: No comfort brake used in the East Link scenario. 2: No freight trains in the East Link scenario

Table 10: Timetable and Simulation parameters for Reference, ATO and NG Brake (Sweden)

5.3.1 Braking rates

Realised braking rates depend on whether the braking action is bounded by an ETCS braking curve or not. If the driver brakes freely, without being bounded by an ETCS braking curve, then we assume they follow a constant deceleration and for all the lines besides the East Link a constant of –0.6 m/s^2 for passenger trains and –0.3 m/s^2 for freight trains have been used. For the East Link and for braking bounded by ETCS the permitted curve is used. We do not assume any changes in the braking force applied between the scenarios. The main reason for this is potential uncertainty of how the drivers brake and how a current educational bias might be corrected as alternative to ATO braking rate benefits.

Fourth, the parameter T_driver is an ETCS parameter that defines the time distance from the intervention curve to the permitted curve. In the Swedish cases, while there exists uncertainty on which driving curve the train drivers follow, the reference scenario assumption is that trains brake following the permitted curve. The ATO scenario assumption is that a train equipped with ATO will be able to follow a braking curve closer to the intervention curve. By changing the T_driver from 4 seconds to 2 seconds for ATO trains, there will be a 2 second difference between manual and ATO driven trains.

Fifth, for NG Brake scenarios, the value of ETCS braking safety adjustment parameters for dry and wet weather are known as Kdry_rst and Kwet_rst. Specifically, Kdry_rst is a speed-dependent correction factor used to calculate emergency braking deceleration on dry rails. It quantifies

performance dispersion for specific braking confidence levels. In collaboration with experts from the NG Brake Work Package in R2DATO, we set Kdry_rst from 0.64 to 0.82, an improvement of 50% as a value of 1 is optimal and represents no limitation on the braking curve.

5.3.2 Running time allowance

In the simulation software, there is a parameter called standard allowance, which represents a mandatory running time allowance that planners add to the simulations. In Sweden, a standard allowance of 3% has been used to cover the driver variation and thus this allowance cannot be used for delay reduction in stochastic or deterministic simulations with manual drivers. There are uncertainties of the validity of the 3% but as there are no other data on the actual driver variation, this parameter has been set to 0% for the ATO scenarios. Note that the assumed delta corresponds to the Dutch case study assumption. For the lines Stockholm Commuter Line, Malmö City Tunnel, and Norrköping-Mjölby there were allowance times in the timetable for 2025. For the East Link 5% was used as it is a planned line.

5.3.3 Headway allowance

Headway allowances were not applied in the Swedish case.

5.3.4 Stopping time

No changes in the stopping times between the scenarios for the GoA2 scenario.

5.3.5 Additional parameters

In the simulations, there is a reaction time to an upgraded signal aspect or movement authority if a train was previously braking towards it or standing still. For the scenarios with manual driving, we assume a reaction time of 2 seconds, while we assume no reaction time for ATO. This assumption is based on the ATO getting the information directly, while the train driver has the risk of looking at other things and might take a few seconds to see the updated signalling message.

In future studies, the driver variation should be studied to be able to accurately model the manual driving for the reference scenario, as the impact of ATO is dependent on the reference scenario. The driving is most likely different on different types of lines (single-track and double-track), time of day, and type of train.

6 APPLICATION - CAPACITY INDICATOR RESULTS

This chapter presents the results of the studies outlined in the previous chapter in terms of capacity indicators. Section 3.2 forms important context for the interpretation of the results, as it explains the applied measurement techniques. Section 6.1 describes results for the Dutch case study (HTD, ATO, NG Brake) and Section 6.2 describes results for the Swedish case studies (ATO, NG Brake). Section 6.3 describes results from an analytical study into the energy consumption effect of different driving strategies using common Dutch train types. Appendix A contains a full report of this study.

6.1 CAPACITY INDICATOR RESULTS (NETHERLANDS)

6.1.1 HTD

Table 11 below lists the Dutch UIC406 compression percentages including headway and running time allowances. Values below 100% imply a feasible timetable, but lower values are preferable from operational stability perspective. Tested line segments are coded with their official station code, as well as a potential addition to denote whether inner or outer tracks are analysed on quadruple track sections. Figure 35 below shows these line segments schematically to provide context.

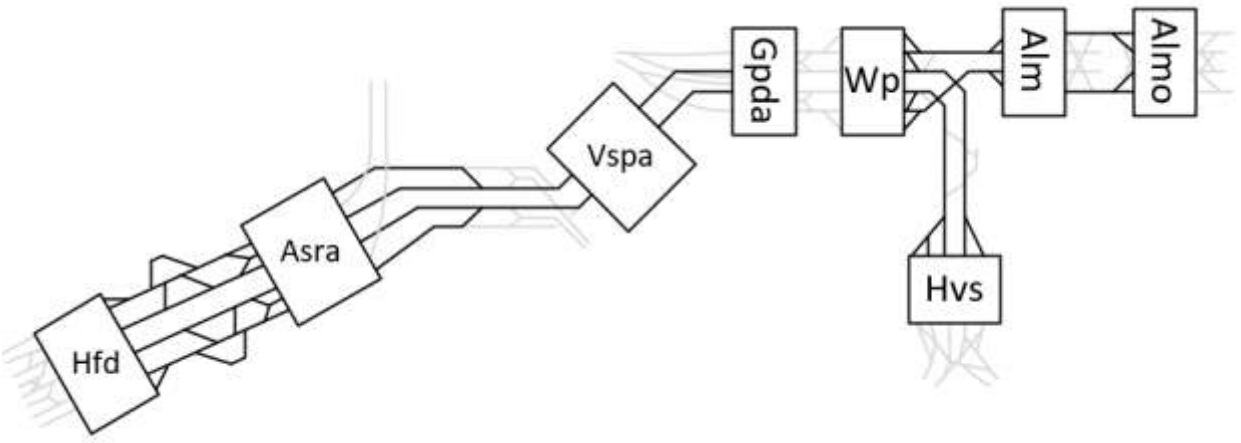


Figure 35: Schematic overview of UIC406 track segments for SAAL corridor (NL)

Scenario	0	1	2	3	4
Axle counter layout	Reference Level 2 layout	Bare minimum axle counters	~50% axle counters removed	~50% axle counters removed	~50% axle counters removed
Number of axle counters	1085	407 (-678)	515 (-570)	-570	-570
Number of blocks	Current Blocks	Current Blocks (Virtual and physical)	Current Blocks (Virtual and physical)	Blocks divided in two virtual blocks if possible	Blocks divided in four virtual blocks if possible

From	To					
Alm	Almo	67.4	67.9 (+0.5)	67.9 (+0.5)	65.2 (-2.2)	63.3 (-4.1)
Almo	Alm	70.0	70.7 (+0.7)	70.7 (+0.7)	66.2 (-3.8)	65.4 (-4.6)
Wp	Alm	90.4	91.3 (+0.9)	91.3 (+0.9)	90.5 (+0.1)	87.7 (-2.7)
Alm	Wp	84.0	84.8 (+0.8)	84.8 (+0.8)	81.8 (-2.2)	81.1 (-2.9)
Vspa	Asra inner	81.7	82.2 (+0.5)	82.2 (+0.5)		
Asra inner	Vspa	85.2	85.9 (+0.7)	85.9 (+0.7)		
Asra inner	Hfd inner	82.7	83.5 (+0.8)	83.5 (+0.8)		
Hfd inner	Asra inner	85.2	85.6 (+0.4)	85.6 (+0.4)		
Asra outer	Hfd outer	94.3	95.0 (+0.7)	95.0 (+0.7)		
Hfd outer	Asra outer	92.7	93.3 (+0.6)	93.3 (+0.6)		
Hvs	Wp	72.7	81.3 (+8.6)	74.2 (+1.5)		
Wp	Hvs	72.7	79.1 (+6.4)	73.7 (+1.0)		
Gpda	Vspa	56.8	64.2 (+7.4)	57.3 (+0.5)		
Vspa	Gpda	53.5	62.1 (+8.6)	54.2 (+0.7)		
Average	**SAAL**	**ref**	**+2.7**	**+0.7**		
Average	**Flevo**	**ref**	**+0.7**	**+0.7**	**-2.0**	**-3.6**

Table 11: UIC406 compression (%) including Dutch planning allowances for HTD

Note: Changes relative to scenario 0 in brackets. All passenger trains have HTD in all reported scenarios.

We draw the following conclusions from these results. First, as can be seen, capacity utilization slightly worsens when going from L2 to HTD without adding new virtual blocks. This is because virtual blocks have a slightly higher interlocking block release time, which lengthens the technical minimal headway. Nonetheless, the small size of this increase suggests that a strong reduction in axle counters is possible from capacity point of view, even when not utilizing the real capacity benefit of HTD by generating smaller virtual blocks.

Second, we observe that the bare minimum of axle counters performs much worse in capacity on the line segments that we assume have non-HTD trains. Specifically, these are the line segments Vspa-Gpda and Wp-Hvs, on which freight trains run twice per hour per direction. Since these trains require axle counters to vacate blocks behind them, this result makes sense. It suggests that an approach where some non-safety-critical track detection components remain at regular intervals, such as in scenario (2), is preferable when non-HTD trains still run on the infrastructure. Figure 36 below shows the effect from scenario 0 to scenario 1 graphically. As can be seen, the removal of many axle counters does not impact the capacity utilization of HTD trains much, but the freight train uses a lot of capacity as it cannot release the virtual blocks behind it, only doing so when it reaches a safety-critical axle counter.

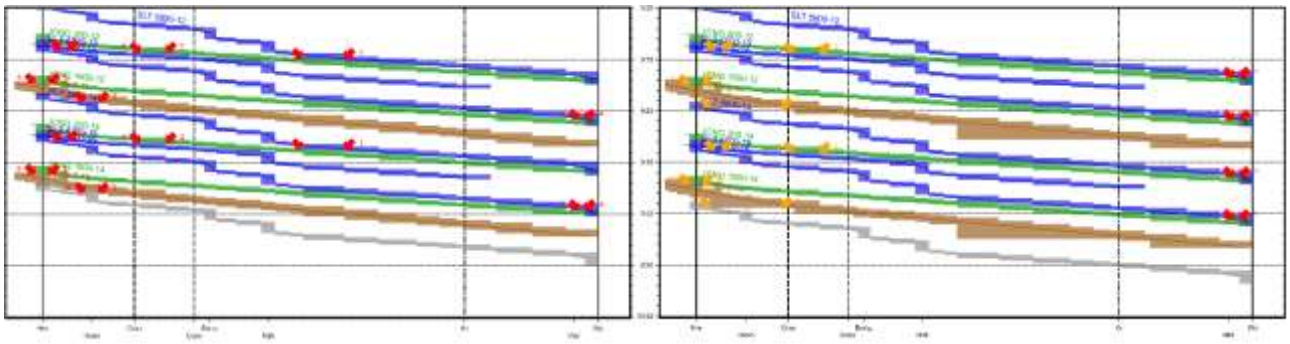


Figure 36: UIC406 compression for Hvs-Wp, reference L2 model (left) vs minimal axle counter HTD model (right)

Third, we see that shorter blocks yield reasonably sized capacity effects of up to a few timetable compression percentage points per hour. We observe diminishing marginal returns as virtual blocks become smaller. Figure 37 below shows the effect from scenario 2 to scenario 4 for the line segment Almo-Alm graphically. As can be seen, the compressed timetable for scenario 4 has more open space left, which enhances operational stability.

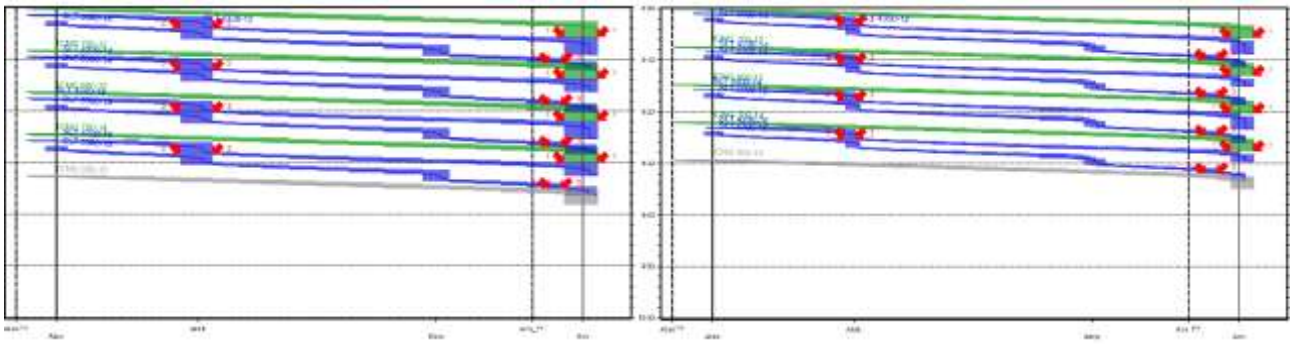


Figure 37: UIC406 compression for line segment Almo-Alm, comparing old block layout (left) to smaller virtual block layout (right)

In addition to the presented scenarios, we studied many more timetable variants on these infrastructure variants, including ones where none of the stopping trains had HTD, or variants where freight trains were rerouted over the part of the infrastructure where we shortened virtual blocks. We do not report them here as we do not economically analyse them. The interested reader can refer to Deliverable FP1-D9.2 (to be published) or FP2-D37.4 (Aoun et al., 2026).

Aside from UIC406 compression, we also perform simulations of delay recovery as a result of an input deterministic delay of 15 minutes at an intermediate station (Almere Poort) on the track section that we constructed infrastructure variants with smaller virtual blocks for. We will not use this for economic analysis, as this 15-minute delay is hard to translate into yearly economic benefits from higher operational stability. Nonetheless, we report these results here as they confirm the benefit HTD has on prevention and recovery of delays. Table 12 below shows these results.

	Delay direction	Number of virtual blocks	Recovery time (within model extent) (s)	No of delayed trains	Total Wp-Almo delay all stops all trains (s)	Energy consumption per train (kWh)
I-1 T-6	Almo	59	1420	9	11248.6	372.6
I-2 T-6	Almo	128	1250	8	10573	373.7
I-3 T-6	Almo	255	1250	8	10179.6	374.8
I-1 T-6	Wp	59	1268	8	5735.8	317.1
I-2 T-6	Wp	128	1268	8	5389.1	306.7
I-3 T-6	Wp	255	908	6	4884.8	303.6
I-1 T-7	Almo	58	1752	10	5319.2	449.2
I-2 T-7	Almo	128	1436	10	4921.2	443.5
I-3 T-7	Almo	254	1425	10	4687.9	446.6
I-1 T-7	Wp	58	1268	8	3939.9	428.2
I-2 T-7	Wp	128	1268	8	3987.4	422.1
I-3 T-7	Wp	254	1268	8	3772.5	423.1

Table 12: Delay recovery after deterministic 15 min departure delay at Almere Poort with different virtual block lengths

We observe that shorter block layouts reduced delay indicator sizes quite strongly. The number of delayed trains decreases by at least 10%, and total delay time can decrease by similar margins. The slight increase in energy consumption for the delay direction Almo was an artifact from one of the delayed trains following a saw-tooth strategy of continuous acceleration and deceleration at high velocity, as new smaller virtual blocks kept this train from a single deceleration to zero and then acceleration to cruising speed again. This suggests a complementary benefit of HTD and DATO techniques that offer driving advice based on surrounding traffic conditions, such as TMS and ATO.

Accordingly, Figure 38 below shows the faster delay recovery time and lower number of delayed trains visually in a time distance diagram, from scenario 2 to scenario 4 in the direction of Almo. Particularly, because blocks are shorter, the traffic jam behind the delayed train at the initial delayed train decreases in length, and the delayed trains can follow each other more closely while recovering. This decreases total delay time and decreases the chance to be impacted by the delay.

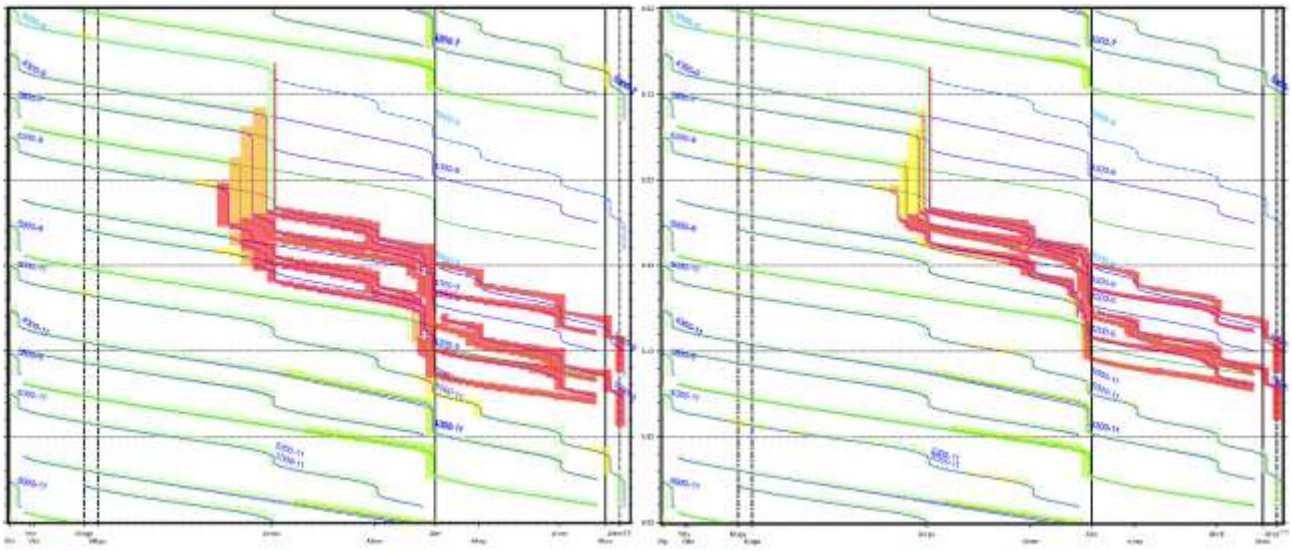


Figure 38: Delay recovery after deterministic 15min departure delay at Almere Poort with different virtual block lengths

We conclude that HTD can offer a sizeable improvement in operational stability. In addition, we conclude that we can save on axle counters (up to about 50%) on the SAAL corridor without sacrificing meaningful capacity. Finally, we conclude that HTD can offer space for further trains per unit of time in specific circumstances, but we refrain from further analysis of this.

6.1.2 ATO

For ATO, we modelled GoA2 and GoA4 on the SAAL corridor. As ATO decreases the standard running time allowance and decreases the technical minimal running time through harder braking, there exists a decision what to allocate this additional time benefit to: lower running time (and the resulting Intermediate Effects), or improved operational stability (and the resulting Intermediate Effects). In this deliverable, for valuing the impacts on the business case, we assumed theoretical running time gains as accruing to running time. While we acknowledge that this is a shortcut, designing a new optimized timetable with ATO allowances and running times would take effort beyond the scope of the capacity simulation study. In addition, ATO does still have an operational stability benefit that we could and did not allocate to running time, which is the 15 seconds decrease in the headway allowance.

Table 13 below shows the running time gains when going from the reference, which is a driver with C-DAS, towards ATO GoA2 and GoA4 respectively. We observe a reduction in running time of 1.97 seconds per kilometre for ATO GoA2. This benefit is slightly higher for stopping trains, reflecting the larger number of scheduled braking actions they carry out. The benefit is much lower for freight trains, reflecting both a lesser number of braking actions and the begrudging omission of running time allowance improvement through the assumption of zero allowances for freight trains in our reference timetable.

Scenario	Train type	ATO GoA 2	ATO GoA 4
Running time	Intercity	-1.65	-1.90

	Stopping	-2.35	-2.67
	Freight	-0.12	-0.14
	All	-1.97	-2.26
Stopping time	Intercity	0	-0.66
	Stopping	0	-0.71
	Freight	0	0
	All	0	-0.67
Total		-1.97	-2.93

Table 13: Running time (s/km) and stopping time (s/km) benefits for ATO

We can also represent the capacity benefit of ATO using UIC406 timetable compression including allowance times. Figure 39 below shows the relative changes in capacity utilization percentage including allowance times compared to the reference manual driver. Most of this effect is driven by the reduction in headway allowance. The additional effect for GoA4 comes from slight further running time improvements due to running closer to the emergency braking curves, as well as the assumed reduction in stopping time.

We observe very sizeable reductions in capacity utilization, ranging from 6 to 12 percentage points. Note that 10 percentage points represent 10% of a full hour, so 6 minutes. This shows that ATO can easily add the timetable space to run one extra train per unit of time or enjoy a large operational stability improvement.

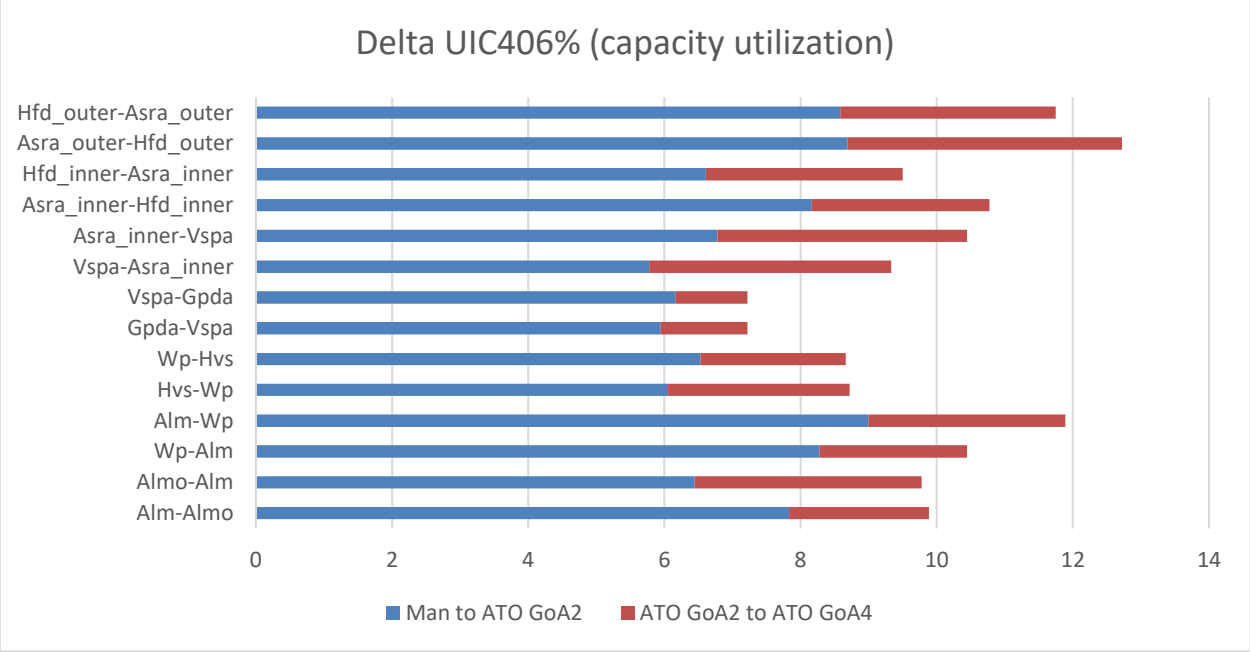


Figure 39: Capacity utilization (including headway and running time allowances) - ATO GoA2 and GoA4 relative to manual driver

Figure 40 below shows an example of the compression effect, comparing the situation with manual drivers on Hvs-Wp to the situation with ATO GoA4. Time-distance diagrams for each train are flatter, implying faster trains. Note that the difference in headway allowances is not pictured.

For time-distance diagrams of simulations with deterministic 15-minute disturbances to prove ATO-induced improvements in operational stability outside of interpretation of UIC406 percentages, we refer to FP1 Deliverable 9.2 (to be published).

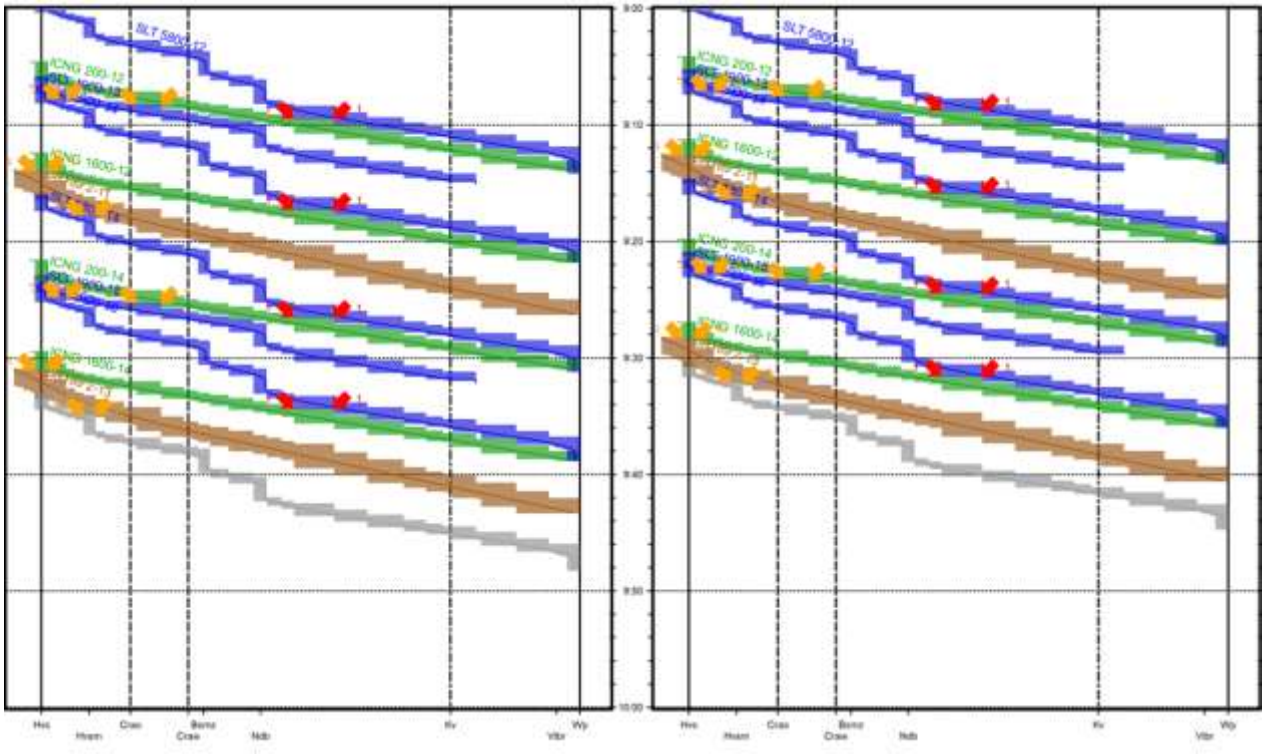


Figure 40: UIC406 compression for line segment Hvs-Wp, comparing human drivers to ATO GoA4

6.1.3 NG Brake

For NG Brake, we identify four NG brake scenarios as of special relevance to the business case. In these scenarios, ATO GoA2 always forms the basis for NG Brake. For FP2-WP17, we simulated an NG Brake that only changes the free braking of the ATO. For FP2-WP18, we simulated an NG Brake that besides ATO also has enhanced ETCS braking curves under dry and reduced adhesion circumstances. For both variations, we simulated an intermediate NG Brake scenario and a maximum achievable scenario. We constrain our economic analysis to running time gains, as we do not know enough about NG Brake yet to assume further parameter changes, such as changes in timetable allowances that could generate operational stability effects. Indeed, FP1-D9.2 (to be published) describes results for UIC406 compressions we did on NG Brake, but we cannot assign the changes in UIC406% to operational stability, as they fully result from running time gains.

Table 14 below shows the results of the simulations expressed in changes in seconds per kilometre. When the adhesion conditions worsen, the running times without NG Brake will increase since the driver will switch to manual driving. With NG brake with ETCS adjustment, the running times of the low adhesion conditions are even better than the ATO without NG Brake. The running times of the low adhesion ATO only NG Brake and all very low adhesion conditions are higher than the dry ATO, but always better than dry manual driving.

In interpreting the results, it is important to note that we assume that ATO without NG Brake is not used in low and very low adhesion conditions by the drivers, since drivers may not trust the system in these conditions while they are responsible to stop at the right position. Hence, for these variants, the reference scenario is the Manual driver in those conditions.

The results show that if NG brake is introduced in the railway system, it has a high potential to prevent punctuality dips due to low adhesion conditions. In addition, we see that local train have a higher direct benefit from NG Brake. This is due to the higher number of braking actions of those services.

Scenario	Train type	Manuel compared to dry manual	ATO GoA2 compared to dry manual	NG Brake intermediate compared to dry manual	NG Brake maximum compared to dry manual	NG Brake incl. ETCS intermediate compared to dry manual	NG Brake incl. ETCS maximum compared to dry manual
Dry	IC	ref	-1.65	-1.81	-1.81	-1.87	-1.87
	Stopping	ref	-2.35	-2.85	-2.85	-3.01	-3.01
	All	ref	-1.97	-2.31	-2.31	-2.43	-2.43
Low adhesion	IC	1.20	-1.07	-1.46	-1.58	-1.62	-1.87
	Stopping	2.78	-0.81	-2.08	-2.50	-2.38	-3.01
	All	2.01	-0.90	-1.75	-2.03	-1.98	-2.43
Very low adhesion [a]	IC	0.67	0.73	-0.81		-0.88	
	Local	7.44	-0.71	-0.04		-0.22	
	All	3.81	2.08	-0.32		-0.43	

Table 14: Change in running times (s/km) for NG Brake

a: for the very low adhesion scenario, the analyzed track segment is limited to the section between Naarden-Bussum and Hilversum, as this is the only area with trees within the ESAAL project extent

For time-distance diagrams of simulations with deterministic 15-minute disturbances to prove NG Brake-induced improvements in operational stability outside of interpretation of UIC406 percentages, we refer to Deliverable 9.2 (to be published).

6.2 CAPACITY INDICATOR RESULTS (SWEDEN)

6.2.1 ATO GoA2

The results from the simulations of GoA2 on the four double-track lines in Sweden are shown in Table 15 below. The values shown are the difference between the GoA2 scenario and the reference scenario. The values shown are the ones that are used for the calculation of impact, a complete set of the results is presented in Deliverable FP1-D9.2 (to be published).

If the additional allowance time is used for shorter running times, there could be gains of up to almost 3 seconds per km for commuter trains in urban areas with frequent stops. The lowest gain is for long-distance trains with around 0.6 seconds per km shorter running times. The shorter running times have not been confirmed with a new timetable and are theoretical but as the lines are double-track lines there is a higher possibility for that compared to single-track lines.

If the additional allowance time instead is used for delay recovery, the stochastic simulation results show a decrease in average delay between 9 and 21 seconds per train. The larger delay reduction is obtained for lines with long-distance trains.

The ATO results show positive effects both for reducing the running times and for delay recovery.

Running time (s)/km	Malmö City Tunnel	Stockholm Commuter Line	Norrköping-Mjölby	Stockholm-Linköping (East Link)
	GoA2-Ref	GoA2-Ref	GoA2-Ref	GoA2-Ref
Commuter	-2.39	-2.86	-1.28	
Regional	-1.89		-0.88	-0.92
Long-distance			-0.83	-0.63
Average delay (s)	-9	-13	-21	-20

Table 15: ATO GoA2 results (s/km) for four Swedish lines

6.2.2 NG Brake

In Table 16 below, the results from the NG Brake scenarios are shown for the line Stockholm-Linköping. The results are from the dry conditions and are the ones that are used in the impact calculation. A complete presentation of the results and the slippery conditions are in Deliverable FP1-D9.2 (to be published).

The NG Brake scenarios show a positive effect if the additional allowance time is used for reducing the running times. The effects are higher for regional trains than for long-distance trains, around twice as much.

If the additional allowance time is used for delay recovery the NG Brake scenario reduces the average delay with 12 seconds and NG Brakes combined with ATO reduces the average delay with 27 seconds.

Running time (s)/km	Stockholm-Linköping (East Link) NG Brake - Reference	Stockholm-Linköping (East Link) ATO + NG Brake - Reference
Regional	-0.40	-1.28
Long-distance	-0.14	-0.75
Average delay (s)	-12	-27

Table 16: NG Brake results (s/km) for four Swedish lines

6.3 Energy Efficiency Study Results

Appendix A describes a self-contained analytical study in the Netherlands of four different energy efficient driving strategies. It assumes the RMS driving strategy as a reference for train drivers without a C-DAS and without regenerative braking. For C-DAS, it assumes the MC driving strategy, and for ATO GoA 2-4, it assumes the EETC driving strategy. In addition, the study assumes unhindered conditions, and it compares the traction energy consumption of the different driving strategies. It uses a Dutch case study on the corridor between Utrecht Central and 's-Hertogenbosch for a long stop distance train (VIRM-6) and between Zaltbommel and 's-Hertogenbosch a short stop distance train (SLT-6).

In general, the results indicate that for short stop distance trains the energy-efficiency of the ATO GoA 2-4 is the same as for the C-DAS driving strategy: the MC is equal to the EETC driving strategy. For larger stop distance trains, the difference between ATO and C-DAS regarding energy consumption depends on the amount of running time allowance provided by the timetable. The scenarios indicate that only for large amount of running time allowance (e.g., > 10%), ATO saves more energy than C-DAS. For instance, 15% running time allowance leads to about 1.6% bigger energy savings for ATO compared to C-DAS.

The results also shows that the relative energy savings of MC and EETC compared to RMS are bigger for short stop distances compared to long stop distances, because relatively a big part of the total driving strategy consists of coasting. Note that for short stopping distances there is no cruising, so the train directly starts to coast at an optimal maximum speed.

The effect of a reduced performance on the acceleration, maximum speed and braking is bigger on ATO and C-DAS compared to manual driving without a C-DAS. A reduction in performance here means that the train does not apply full traction or braking, but in accordance with the performance that is set. For instance, a performance of 90% means that the train applies maximum 90% of the traction and force, and power. This means that the difference in energy savings between ATO/C-DAS and manual driving decreases significantly if the performance is reduced. For instance, if the performance is reduced to 50%, the energy consumption of ATO and C-DAS is almost equal to manual driving without C-DAS, while a performance of 100% leads to a difference of 10% in energy consumption. In general, a lower performance leads to a higher energy consumption, because more time is needed to accelerate and to brake the train.

The effects of varying gradients have an impact on the driving strategies. However, results show instability issues during cruising below the speed limit. This is caused by the single-phase Radau pseudospectral method that is applied as algorithm to solve the optimal control problems

(Scheepmaker, 2020a). Varying speed limits do not influence the results significantly in terms of relative difference in energy savings of ATO, C-DAS and manual driving without C-DAS.

Finally, the results indicate that 1% extra energy savings can be achieved if 10% of the train drivers will use C-DAS compared to manual driving without C-DAS. Therefore, it is important to stimulate train drivers to use their C-DAS if it is available.

The study in Appendix A recommends that future research should consider realistic delays of trains to investigate the difference between ATO, C-DAS and manual driving. Especially for ATO, there may be a lot of gains to be achieved in disturbed situations, especially if the ATO receives real-time information from a TMS (Traffic Management System) regarding surrounding (delayed) trains. For instance, stochastic simulation runs can be applied to get insight in disturbed situations. Such research first requires software development to include the different driving strategies as selectable in timetabling and simulation.

Future research can also consider different train types with the driving strategies. For example, the effect of high-speed trains and freight trains is missing in the current research, while they consume a large amount of energy. In addition, the stopping distance is larger for these train types, and for freight trains the rolling resistance is much bigger than for normal regional or long-distance passenger trains. Therefore, cruising at an optimal speed below the speed limit may be more optimal for these trains.

Finally, in future research, another method can be used to compute the driving strategies, that does not suffer instability issues due to varying gradients. This can be a direct or indirect solution method, or even heuristics (Scheepmaker, et al, 2017).

7 APPLICATION – VALUATION OF IMPACTS

In this chapter, we value the effects on capacity indicators reported in Chapter 6, using the extensive description and definition of BuCa value indicators through intermediate effects in sections 3.3 and 3.4.

The structure of this chapter is as follows. First, Section 7.1 describes the parameter inputs, assumptions and methods used to translate values towards economic and financial impacts. Next, section 7.2 reports the results of our calculations for HTD, ATO and NG Brake. We devote special attention to the valuation of capacity-induced economic and financial impacts of HTD, ATO and NG Brake for the Dutch use case, as we performed semi-quantitative value mapping on it, in accordance with the BuCa methodology developed in D32.1 (van den Berg et al., 2026). This exercise valued qualitative effects in addition to the effects we were able to quantify, seeking to paint a comprehensive picture of the impact of these DATO techniques from capacity point of view. Finally, Section 7.3 describes conclusions of our exercise of applying the interface matrix to our own capacity simulations.

7.1 PARAMETER INPUTS

7.1.1 The Netherlands

We gathered inputs on number of forecasted future passengers entering and exiting per station per train in the future timetable we simulate. We combine this with sources on the value of travel time, delays, and track adhesion condition probabilities, as well as a set of rough assumptions on the value of rolling stock and staff cycles.

7.1.1.1 The number of travellers

For the SAAL case, we used the passenger prognosis of 2040 to calculate the passenger benefits. The passenger prognosis was for a standard working day and based on the mobility development WLO (Welvaart en Leefomgeving) low 2040 (Ritsema van Eck et al., 2025) forecast, which is their low-end passenger trip demand prediction. Namely, given current knowledge, the low forecast seems most likely. A factor 300 multiplies the values of passengers per train series per day to the full year.

7.1.1.2 Attracting new travellers

For this study, we follow the “rule of half” described in Section.4.1.4 (Small & Verhoef, 2007; de Jong, 2018). In other words, we assume that shorter running times will lead to travel time welfare gains for an average new passenger equal to half the value of travel time gains for an average existing traveller. For the trip time, we use the average trip duration from the passenger demand forecast, which was 34 minutes and 4 seconds. To account for travelling outside of the scope of the SAAL study area, we estimate that 50% of the trip duration of new trips is within the SAAL area. We base this assumption on the average time of a train in the SAAL area, which was 22 minutes and 17 seconds. Therefore, it is reasonable to assume that the average new trip will be within the area of SAAL for 50%.

7.1.1.3 Valuation of travel time

The Netherlands Institute for Transport Policy Analysis or *Kennisinstituut voor Mobiliteit* (KiM) regularly researches and updates their guidelines on value of train travel time. For this study, we use a value of €10.08 per hour for travel time (Kouwenhoven et al., 2023). Following standard theory, we value Agglomeration effects as 15% of the VOT benefits for existing travellers. To simplify our work, we do not correct for higher perceived value of stopping times yet, deferring this to future research.

7.1.1.4 Valuation of delays

The KiM also offers guidance for the difference in measured travel time and experienced travel time by the traveller. Most recently, they suggested multiplying the value of travel time by a factor 4 for delays (Warffemius, 2015).

For this study we assume that by increasing the operational stability through additional available headway time, measurable through UIC406 compression and verifiable through deterministic simulation of delay recovery, the punctuality curve will shift, which allows inference on changes in delay time. Section 3.2.2.1 explains the logic behind this method. The method requires an assumption on how many headway conflicts the average traveller is likely to encounter during their trip. Based on expertise, we assume that the average traveller is likely to encounter at least one headway conflict, especially on the dense part of the Dutch railway network which contains SAAL. Therefore, we assume that every traveller will have one opportunity to benefit from shorter headways, and thus experience one beneficial shift in punctuality.

7.1.1.5 Valuation of shorter cycle times

To be able to estimate the cost savings on staff and rolling stock, we have made very rough estimates on the cost of rolling stock and staff per train-km. The accuracy of these estimates is not high. Note that effects on the cost of staff that we measure here only pertain to the effects as a result of potentially shorter cycle times. We do not measure the direct effect of DATO on staff costs or rolling stock costs.

First, for rolling stock, we roughly assume that a single passenger train unit will cost about 1 million Euro per year in depreciation and maintenance together. Since multiple units are usually combined on the SAAL corridor, this means we assumed 2 million Euro for a trainset per year.

For a rough estimate to scale the effects on staff costs, we roughly assumed the following. First, we assumed that on the SAAL corridor, at least two staff members will be present on a train. For any direct staff hour on the train, the staff member must work some additional time off the train, due to other tasks like waiting, walking time, breaks and travel. We assume this as a factor of 1.7, i.e., each hour on the train leads to 42 minutes of working time off the train. Second, we assumed that for each staff member, additional staff must be hired to cater for training, sickness, operational robustness and holidays. We assume this as a factor 1.3, i.e., each hour on the train leads to 18 minutes of additional staff hours used for training, operational robustness, sickness, and holidays. Third, we do not incorporate any savings on administrative staff, staff facilities, or management. Finally, we assume an hourly rate of 45 euros per staff member: 50 euros for the driver, 40 euros for the train attendant. This leads to a direct saving of 1 hour being worth roughly 200 euros worth of staff costs.

7.1.1.6 Valuation of adhesion impact

Low adhesion conditions occur sparsely. For this study, we estimate low adhesion conditions occur on 5% of the rides per year. This is based on the knowledge that November is a month where punctuality is significantly affected by low adhesion due to fallen leaves on known parts of the railway network. Figure 41 below underpins this by showing punctuality data per month for the Netherlands. The number of days was estimated on half of the days in November plus some additional occurrences during the year due to spring storms, morning dew and rain after a dry period.

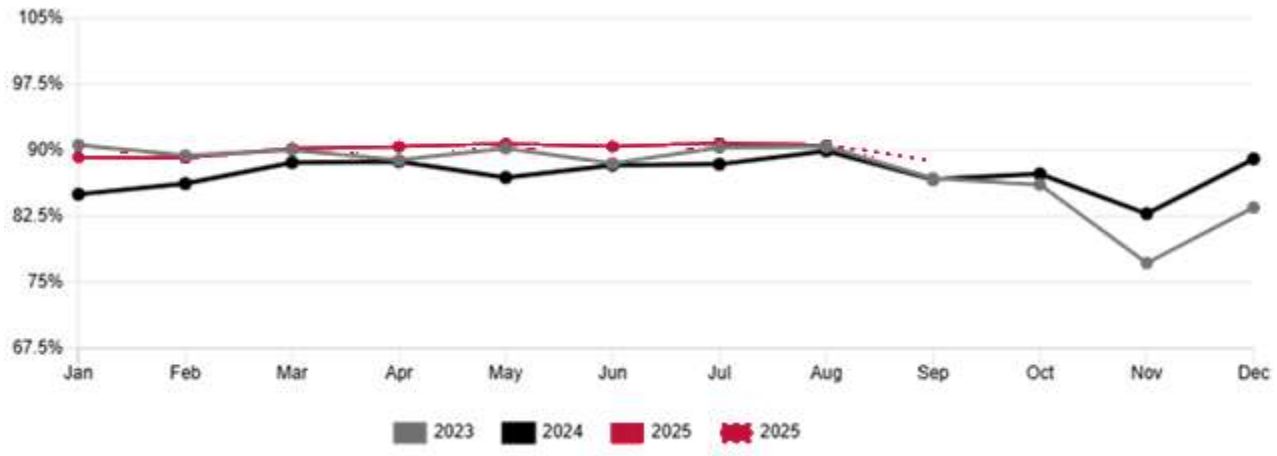


Figure 41: 3-minute punctuality for passenger trains in the Netherlands, 2023-2025

Note: values for the year 2025 were partly preliminary

We estimate very low adhesion conditions to occur 6 days per year. Most of these, too, are in November, but also could occur after dry periods and a spring storm. These 6 days represent 1.6% of the yearly train rides. Admittedly, the values for low and very low adhesion over time are rough estimates for the Dutch situation. Further research is required to increase the accuracy of this number and effects across Europe.

From the measurements on running time gains under low and very low adhesion per DATO technique, we assume 50% of the running time gains to be used for operational stability under low adhesion conditions and 100% under very low adhesion.

7.1.2 Sweden

In the Swedish study, the impacts have only been calculated for the value of time for passengers in the different lines simulated. For these calculations the number of travellers, type of travellers, value of time, and the change in travel time are needed. The changes in travel time and the delay reduction are the results from FP1 WP9 and have been used. In further studies a more detailed calculation could be made as there are several cost values available from Trafikverket (2024).

7.1.2.1 Number of travellers

In Sweden, the infrastructure manager Trafikverket provides prognosis of future traveller numbers. This contains boarding and alighting numbers per station and train line. The data consists of type of traveller between each node in the railway network as well as which line. Based on the type of line, the train type could be identified. This information can be used to calculate the saved travel time on

the simulated scenarios. The data is provided for 2019 (reference value) and 2045. The number of travellers is given for an average day and if multiplied by 320 it will be an annual value.

7.1.2.2 Valuation of travel time

In Sweden the valuation of travel time is dependent on the mode of transport and the type of travel. There also distinctions for connecting trips, delays, and changes of travel mode. Delay time is valued 3.5 times the value of travel time. The value of normal travel time with trains are the following for year 2019 and 2045 (Trafikverket, 2024), see Table 17 below.

	2019	2045
Private – Long distance	94 SEK (8.3 EUR)	127 SEK (11.2 EUR)
Private – Regional and commute	89 SEK (7.8 EUR)	120 SEK (10.6 EUR)
Private – Regional and other	68 SEK (6.0 EUR)	92 SEK (8.1 EUR)
Business – Long distance	331 SEK (29.1 EUR)	445 SEK (39.2 EUR)
Business – Short distance	331 SEK (29.1 EUR)	445 SEK (39.2 EUR)
SEK EUR Conversion rate 0.088 (2024-10-14)		

Table 17: Value of Time for different types of travellers in Sweden

7.1.2.3 Process

Two different usages of the additional allowance time have been calculated. The first usage is to run the trains faster and reducing the travel time. This has not been confirmed by an actual timetable. The societal benefit of this is calculated between stations with passenger exchange. The number of a certain type of passenger is multiplied by their value of time and the travel time gain. The calculation is done by train type. The values were converted from SEK to EUR according to the exchange rate of 0.088.

The second usage of the allowance time is to reduce delays. The calculation of reduction of delays is done by multiplying the average number of onboard passengers (per type) with their respective value of time and the average delay reduction per train. It is assumed that each passenger travels twice per day. Delay time is valued 3.5 times the value of time due to the inconvenience and thus the results is multiplied by 3.5.

There are limitations to these calculations. For example, the number of passengers is uncertain between stations, but they give an indication of the societal benefits of the DATO concepts on three different lines. The time values used are the level of 2019 and the number of passengers is also from 2019. However, the number of passengers for the East Link is from 2045, as that line is yet to be completed.

7.2 VALUATION OF IMPACTS - RESULTS

The results for the capacity simulations from Chapter 6 can be quantified with the parameters described in Section 7.1. Here, we shift from discussing the impacts per use case, and instead discuss the impacts per DATO concept first, then per country. The impacts are always valued for one individual year. Net present valued lifespan effects are therefore likely much higher, as all impacts have those effects over the complete lifetime of the system. We do not include common economic principles such as net present value of developments in this exploratory economic analysis given existing uncertainties on the migration phase towards DATO, which we also did not yet explore through specific roll-out phases in the simulation study. We leave these gaps for future research.

In addition, when considering the list of 14 BuCa value indicators, our limited resources only allowed us to quantitatively estimate a few of them. For the Netherlands, we did try to value the qualitative effects for the separate techniques that are the result of traffic changes. We offer three contextual notes to this exercise.

First, we note that the value estimates on effects other than travel time gains and agglomeration effects are all rough estimates, some with very high uncertainty and based on limited expertise. Hence, we recommend strictly taking those results as illustrative only.

Second, we note that there still exist other effects. Indeed, this Deliverable remains confined to discussing traffic-change induced effects and does not seek to estimate direct effects such as implementation costs or human factors effects. Deliverable 32.1 (van den Berg et al., 2026) is the document where an integration towards a complete business case happens.

Third, the methodology we use to estimate and sum up effects is *Semi-Quantitative Value Mapping*, a method founded in Multi-Criteria Analysis that Deliverable 32.1 (van den Berg et al., 2026) ended up recommending for DATO Business Case analysis at this stage. For further explanation and justification of this methodology, we refer to that Deliverable. In this Deliverable, we only present results.

The rest of this Section has the following structure. We first discuss HTD results, which were only analysed for the ESAAL (NL) use case, including a semi-quantitative value mapping. Next, we discuss ATO results, first for the ESAAL (NL) use case including a semi-quantitative value mapping, then for the four Swedish cases. Finally, we discuss NG Brake results, first for the ESAAL (NL) use case including a semi-quantitative value mapping, then for the Southern Main Line (SE) case.

7.2.1 HTD

7.2.1.1 Netherlands

Per the interface matrix, HTD has no running time or stopping time effect, while it does have potential operational stability and number of trains per unit of time effects. We assume here that we fully distribute the benefits of a lower UIC compression percentage towards operational stability instead of a higher number of trains per unit of time, since no extra trains were added in the HTD scenarios. Consequently, Table 18 below shows the economic benefits on value of travel time and agglomeration effects for the HTD variants that got shorter virtual blocks, relative to the HTD reference scenario 2, where the number of blocks was kept the same as in the ETCS L2 reference scenario.

Scenario	3	4
Axle counter layout	50% axle counters removed	50% axle counters removed
Number of axle counters	-139	-139
Number of blocks	Blocks divided in two virtual blocks where possible	Blocks divided in four virtual blocks where possible
Agglomeration effects	EUR 0.1M	EUR 0.1M
Value of travel/transport time – new travellers	EUR 0.1M	EUR 0.3M
Value of travel/transport time – reduced delays	EUR 0.5M	EUR 0.8M
Total business impact per year	**EUR 0.7M**	**EUR 1.2M**

Table 18: Economic impacts of HTD, Flevo shorter virtual blocks cases

Using the number of passenger-kilometres travelled on the *Flevo* part of the SAAL corridor, we can extrapolate these economic results to the full SAAL corridor. Table 19 below shows these results. As can be seen, there is layeredness in the potential economic benefits for HTD that stem from capacity effects.

Concretely, the first two scenarios have a negative result. This is because the capacity slightly decreases if the block layout is kept the same. Since the cost of virtual blocks is an order of magnitude lower than that of a physical block, we deem it most logical to continue the business case with scenario 4, where virtual blocks are sized ideally at just a quarter of the size of the original axle-countered blocks, where the infrastructure allows it. The other scenarios may occur in a migration phase during the introduction of HTD.

Scenario	1	2	3	4
Axle counter layout	Bare minimum axle counters	50% axle counters removed	50% axle counters removed	50% axle counters removed
Number of axle counters	-678	-570	-570	-570
Number of blocks	Current Blocks (Virtual and physical)	Current Blocks (Virtual and physical)	Blocks divided in two virtual blocks where possible	Blocks divided in four virtual blocks where possible
Agglomeration effects	EUR -0.5M	EUR -0.1M	EUR 0.4M	EUR 0.6M
Value of travel/transport time – new travellers	EUR -1.0M	EUR –0.3M	EUR 0.7M	EUR 1.4M

Value of travel/transport time – reduced delays	EUR -3.7M	EUR –0.9M	EUR 2.5M	EUR 4.3M
Total business impact per year	**EUR -5.2M**	**EUR –1.3M**	**EUR 3.6M**	**EUR 6.3M**

Table 19: Monetized selective economic impacts of HTD

Although we have not quantified all BuCa value indicators, we applied semi-quantitative value mapping within a small group of experts to still attempt to value the effects on the other unquantified indicators. This method corresponds to the BuCa methodology explained in D32.1 (van den Berg et al., 2026).

Assuming successful scenario 4 implementation, we estimated the relative effect sizes on constructed attribute scales in Table 20 below. The travel time is the highest value and therefore set to 1. The societal travel time gains are the highest followed by the ticket sales from the newly attracted travellers. The other effects are either 0 or relatively small compared to the travel time gains and ticket sales.

Business impact	**Effect of HTD**	**Effect size[a]**
Other welfare effects	Effect of modal shift	0.1
Agglomeration effects	Quantified (0.6M EUR)	0.15
Passenger welfare	HTD adds an extra 'traffic jam decreases in size and more quickly, so slightly higher benefit than for ATO. We ignore less track component failures' effect.	0.15
Value of travel/transport time	Quantified (5.7M EUR)	1
External environmental effects	Effect of modal shift	0.15
Ticket sales, Economies of scale	Due to the increasing number of travellers. Estimate using total yearly ticket revenue and number of passengers: 4.3M EUR	0.75
Fleet size of rolling stock	No effect is expected	0
Vehicle maintenance	Less unplanned braking actions from operational stability	0.01
Staff costs	No effect is expected	0
Labour conditions	Labour conditions are expected to be improved due to less delays	0.15
Energy costs	judged as very small effect based on deterministic delay test (only few kWh saved)	0.01

Infrastructure access fees	Infra access fees per ticket sold ratio of 16.8/100. Based on extra ticket sales, estimated 722,400 EUR.	0.042
Infrastructure investments	No effect is expected (note: direct axle counter savings are not a traffic-induced effect)	0
Infrastructure maintenance	No effect is expected (note: direct axle counter savings are not a traffic-induced effect)	0

Table 20: Overview of BuCa value capacity indicator impacts of HTD scenario 4, illustrative guesses on qualitative effects

a: Effect size is a utility score from 0 to 1. Since we have some monetary estimates, we assume that the highest effect gets a value of 1 and relate our other estimates to this value.

Representing the effect sizes in a semi-quantitative value mapping yields the trade-off in Figure 42 below. Within semi-quantitative value mapping, these effect sizes get local weights according to assumed stakeholder trade-offs and then global weights according to their relative total effect sizes. As can be seen, the bulk of the traffic-induced benefits of HTD are welfare effects that accrue to society. Again, we note that direct cost effects of HTD – also the beneficial one from a reduced number of axle counters – are not included in this analysis.

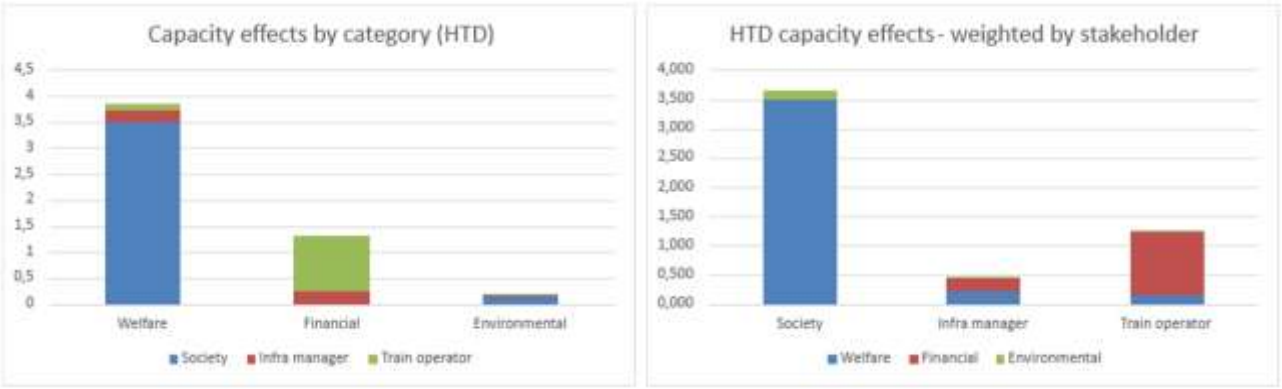


Figure 42: Semi-quantitative value mapping by effect category and stakeholder (HTD)

7.2.2 ATO

7.2.2.1 Netherlands

From the running time gains, we calculate the travel time gains by multiplying each existing traveller with their respective travel time gains. Table 21 below shows the resulting generalized percentages of travel time reduction. The running time gains show huge potential, since the running time gains could be scaled from SAAL to the complete Netherlands. This could have a major effect on economic welfare and regional mobility in the Netherlands.

In addition to the running time gain from faster braking and a decrease in the running time allowance, we assume that the headway allowance improvement for ATO accrues to operational stability instead of the number of trains per unit of time. Congruously, since the source of operational stability

gains and the source of running time gains are independent, the benefits of reduced delays and travel time gains are independent, too, and may be summed. We do this in Table 22 below, which shows all our monetized impacts for ATO.

Scenario	Manual driving with DAS	ATO GoA 2	ATO GoA 4
Running time	ref	-5.1	-5.7
Stopping time	ref	0	-9.8
Total	ref	-4.5	-6.2

Table 21: Relative travel time gains (%) of ATO compared to manual driving

Business impacts per year	ATO GoA2	ATO GoA4
Agglomeration effects	EUR 3.1M	EUR 3.8M
Value of travel/transport time [new travellers] – Reduced travel time	1.0M	1.4M
Value of travel/transport time [new travellers] – Reduced delays	1.1M	1.1M
Value of travel/transport time [new travellers] – Value of extra travellers	EUR 5.3M	EUR 6.2M
Value of travel/transport time [existing travellers] – Reduced travel time	EUR 9.4M	EUR 12.9M
Value of travel/transport time [existing travellers] – Reduced delays	EUR 5.9M	EUR 5.9M
Reduction in rolling stock costs	EUR 1.7M	EUR 2.5M
Reduction in staff costs	EUR 0.9M	EUR 1.4M
Total	**EUR 26.3M**	**EUR 32.7M**

Table 22: Monetized selective economic and financial impacts for ATO

Table 23 below shows the estimated effect sizes using semi-quantitative value mapping explained in D32.1 (van den Berg et al., 2026) with constructed attributes. It shows that the travel time gains and increased ticket sales have the biggest relative effect for ATO GoA2 and 4. Other effects are smaller or are not present. We see that effects for ATO GoA4 are slightly different, but still comparable.

Business impact	Effect of ATO GoA2	Effect size[a] ATO GoA2	Effect size[a] ATO GoA4
Other welfare effects	Effects from modal shift	0.1	0.1
Agglomeration effects	Quantified (3.1M EUR GoA2, 3.75M EUR GoA4)	0.15	0.15
Passenger welfare	Increased operational stability. Does not change from GoA2 to GoA4 so the relative effect size decreases, as a value of 1 for GoA4 is higher.	0.1	0.08
Value of travel time	Quantified (20.6 M EUR GoA2, 25.0M GoA4)	1	1
External environmental effects	Effect of modal shift	0.15	0.15
Ticket sales, Economies of scale	Due to the increasing number of travellers. Estimate using total yearly ticket revenue and number of passengers: 18.95M EUR	0.79	0.74
Fleet size of rolling stock	Quantified (2.5M EUR)	0.08	0.10
Vehicle maintenance	We do not know how to value the consistent higher braking (bad effect) versus the less unplanned braking actions from headway allowance benefit (good effect). We guess that the number of unplanned brakes decreases marginally, while consistent higher braking is constant, but individual braking actions usually dominate the strength of braking in costs.	0	0
Staff costs	Quantified (1.4M EUR)	0.04	0.05
Labour conditions	Labour conditions are expected to be improved due to less delays for train staff. For GoA4, only 1 out of 2 assumed train staff remains, so the benefit also gets halved. On the other hand, D32.4 (Lo et al., 2026) suggest an increase of workload might be experienced by the train dispatchers, though they attribute this to an underdeveloped TMS.	0.1	0.04
Energy costs	Due to alteration of the running time allowance, energy consumption increases, but less unplanned braking actions lead to higher energy savings. Net effect is unknown.	0	0
Infrastructure access fees	Infra access fees per ticket sold ratio of 16.8/100. Based on extra ticket sales, estimated 3,183,600 EUR.	0	0
Infrastructure investments	No effect is expected in this case, although a case may exist for a prevented 4-7B EUR metro extension.	0	0
Infrastructure maintenance	Question mark per similar logic as for vehicle maintenance	0	0

Table 23: Overview of BuCa value indicator impacts of ATO, valued using semi-quantitative value mapping, illustrative guesses on qualitative effects

a: Effect size is a utility score from 0 to 1. Since we have some monetary estimates, we assume that the highest effect gets a value of 1 and relate our other estimates to this value.

Representing the effect sizes in a semi-quantitative value mapping yields the trade-offs in Figure 43 below. Within semi-quantitative value mapping, these effect sizes get local weights according to assumed stakeholder trade-offs and then global weights according to their relative total effect sizes. As can be seen, the bulk of the traffic-induced effects of ATO are welfare benefits that accrue to society, while the train operator also experiences quite strong financial benefits.

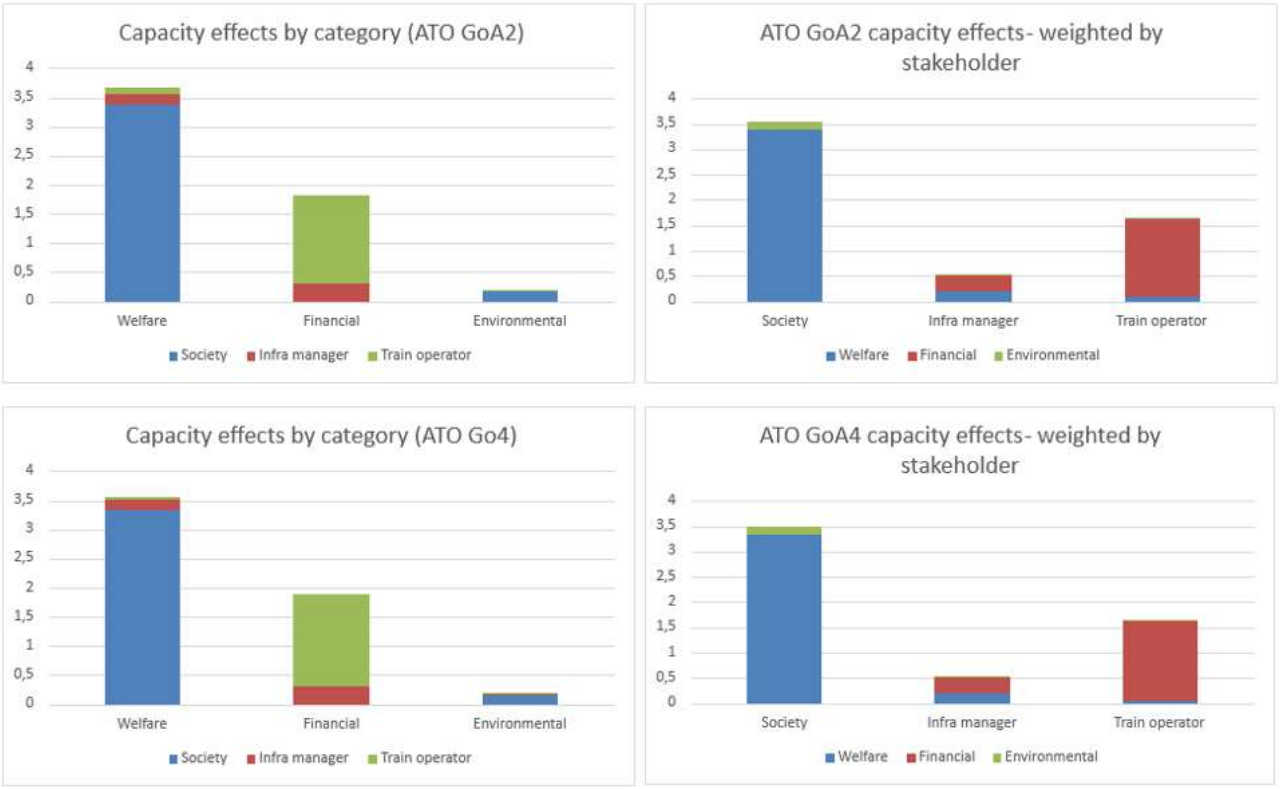


Figure 43: Semi-quantitative value mapping by effect category and stakeholder (ATO)

Note: the y-axis is not comparable between GoA2 and GoA4, as their constructed attribute scale from 0 to 1 has different benchmarks – in general, effects for GoA4 are 20-25% larger than for GoA2

7.2.2.2 Sweden

For the four double-track lines in the case study, it is assumed that the running time decrease with ATO GoA2 could be used for travel time decrease. No specific timetables for the ATO GoA2 scenario were made, but this should be done in future studies. Thus, the additional allowance time made available by the ATO settings could be used for travel time decrease or used for delay reduction in the stochastic simulations. A new timetable needs to be planned to estimate potential running time gains. For all scenarios there are positive value of time by introducing ATO GoA2.

The additional allowance time varied from 0.6 s/km for long-distance trains up to 2.9 s/km for commuter trains on the Stockholm Commuter Line.

In Table 24, the calculated values of time for one year are presented. For all the shorter double-track lines there is a societal benefit to use the additional allowance to decrease delays rather than decrease the travel time. But for the line Stockholm-Linköping the reduced travel time is more

beneficial. There is a large difference in the length between the lines and value of reduced travel time increases with the length, but the effects of reduced delays might not do that.

Another option would be to use the additional allowance time for energy savings with more coasting or to alternate between different modes based on the current situations or time of day.

Per annum	Malmö City Tunnel (14 km)	Stockholm Commuter Line (11 km)	Norrköping-Mjölby (64 km)	Stockholm-Linköping (East Link) (195 km)
Value of time - Reduced travel time	EUR 0.86M	EUR 2.50M	EUR 1.16M	EUR 4.62M
Value of time – Reduced delays	EUR 0.95M	EUR 3.59M	EUR 1.55M	EUR 2.35M
Average number of passengers per direction and day	20 000	56 000	10 000	29 000

Table 24: Benefits of ATO compared to manual driving

7.2.3 NG Brake

7.2.3.1 Netherlands

For NG Brake, we quantify four NG brake scenarios. In these scenarios there is always ATO GoA2 as a basis for NG Brake. For this analysis, we assume that ATO is not used in low and very low adhesion conditions by the drivers, since drivers do not trust the system in these conditions.

The effects of the increased braking in dry conditions are calculated towards travel time decrease and the travel time decrease of the low and very low adhesion conditions are calculated toward operational stability (reduced delays) because the timetable in the Netherlands does not especially cater for these conditions. Table 25 below shows the generalized travel time reductions, taking traveller numbers into account. The running time of the manual reference increases with low and very low adhesion because ATO is switched off and the driver must brake manually.

Scenario	Reference scenario	Compared to dry manual	NG Brake intermediate	NG Brake maximum	NG Brake incl. ETCS intermediate	NG Brake incl. ETCS maximum
Dry	ATO	-4.5	-5.2	-5.2	-5.5	-5.5
Low	Manual	4.4	-4.0	-4.6	-4.5	-5.5
Very low	Manual	5.2	-3.6	Not simulated	-4.0	Not simulated

Table 25: Relative decrease in travel times (%) for NG Brake scenarios

Besides the direct gains in travel time and operational stability, the availability of NG Brake also attracts new travellers, create agglomeration effects, and saves train staff and rolling stock. If we monetize the effects and compare this to the references, we see overall positive benefits that add up for 6.6M Euros to 8.0M Euros despite low and very low adhesion conditions not occurring often. Table 26 below shows these monetized impacts.

Business impact per year		**NG Brake**	**NG Brake max**	**NG Brake + ETCS**	**NG Brake max + ETCS**
Agglomeration effects	Agglomeration effects	EUR 0.8M	EUR 0.8M	EUR 0.9M	EUR 0.9M
Value of travel/transport time [extra travellers]	Extra number of trips - travel times dry	0.17M	0.17M	0.23M	0.23M
Value of travel/transport time [extra travellers]	Extra number of trips - Reduced delays low adhesion	0.10M	0.10M	0.10M	0.11M
Value of travel/transport time [extra travellers]	Extra number of trips - Reduced delays very low adhesion	0.03M	0.03M	0.03M	0.03M
Value of travel/transport time [extra travellers]	Value of extra travellers	EUR 0.8M	EUR 0.8M	EUR 0.9M	EUR 1.0M
Value of travel/transport time [existing travellers]	Value of time - Reduced travel time	EUR 1.5M	EUR 1.5M	EUR 2.1M	EUR 2.1M
Value of travel/transport time [existing travellers]	Value of time – Reduced delays low adhesion	EUR 1.8M	EUR 1.9M	EUR 1.9M	EUR 2.1M
Value of travel/transport time [existing travellers]	Value of time – Reduced delays very low adhesion	EUR 1.2M	EUR 1.2M	EUR 1.3M	EUR 1.3M
Fleet size of rolling stock	Rolling stock Savings estimate	EUR 0.3M	EUR 0.4M	EUR 0.3M	EUR 0.4M
Staff costs	Labour cost saving estimate	EUR 0.2M	EUR 0.2M	EUR 0.2M	EUR 0.2M
Total		**EUR 6.6M**	**EUR 6.8M**	**EUR 7,6M**	**EUR 8.0M**

Table 26: Monetized selective economic and financial impacts of NG Brake

We conclude that the basic NG Brake system i.e., without maximal development quality nor ETCS braking curve integration, already cashes in the bulk of the potential benefits. This suggests that a faster roll-out of a not optimized, cheaper system is preferable over a slow roll-out of an optimized, more expensive system, or at least supports phased roll-out with regards to the capacity benefits.

Although we have not quantified all BuCa value indicators, we next applied semi-quantitative value mapping within a small group of experts to still attempt to value the effects on the other unquantified indicators. This method corresponds to the BuCa methodology explained in D32.1 (van den Berg et al., 2026).

Assuming successful scenario “NG Brake” implementation, we estimated the relative effect sizes on constructed attribute scales in Table 27 below. The travel time is the highest value and therefore set to 1.

Business impact	Effect of NG Brake	Effect size
Other welfare effects	Effect of modal shift	0.10
Agglomeration effects	Quantified (795,000 EUR)	0.15
Passenger welfare	Increase of operational stability	0.11
Value of travel/transport time	Quantified (5.3M EUR)	1
External environmental effects	Effect of modal shift	0.15
Ticket sales, Economies of scale	Due to the increasing number of travellers. Estimate using total yearly ticket revenue and number of passengers: 4.3M EUR	0.81
Fleet size of rolling stock	Quantified (300,000 EUR)	0.06
Vehicle maintenance	We do not know how to value the consistent higher braking (bad effect) versus the less unplanned braking actions from headway allowance benefit (good effect). We guess that the number of unplanned brakes decreases marginally, while consistent higher braking is constant, but individual braking actions usually dominate the strength of braking in costs.	0
Staff costs	Quantified (300,000 EUR)	0.04
Labour conditions	We expect improved labour conditions due to less delays for train staff and less stress during braking for the driver.	0.11
Energy costs	More time would be available for energy efficient driving. Therefore, we expect a positive effect.	0.02
Infrastructure access fees	No effect is expected	0
Infrastructure investments	No effect is expected	0

Infrastructure maintenance	Question mark per similar logic as for vehicle maintenance.	0

Table 27: Overview of BuCa value indicator impacts of NG Brake, valued using semi-quantitative value mapping, illustrative guesses on qualitative effects

a: Effect size is a utility score from 0 to 1. Since we have some monetary estimates, we assume that the highest effect gets a value of 1 and relate our other estimates to this value.

Representing the effect sizes in a semi-quantitative value mapping yields the trade-offs in Figure 44 below. Within semi-quantitative value mapping, these effect sizes get local weights according to assumed stakeholder trade-offs and then global weights according to their relative total effect sizes. As can be seen, the bulk of the traffic-induced effects of ATO are welfare benefits that accrue to society.

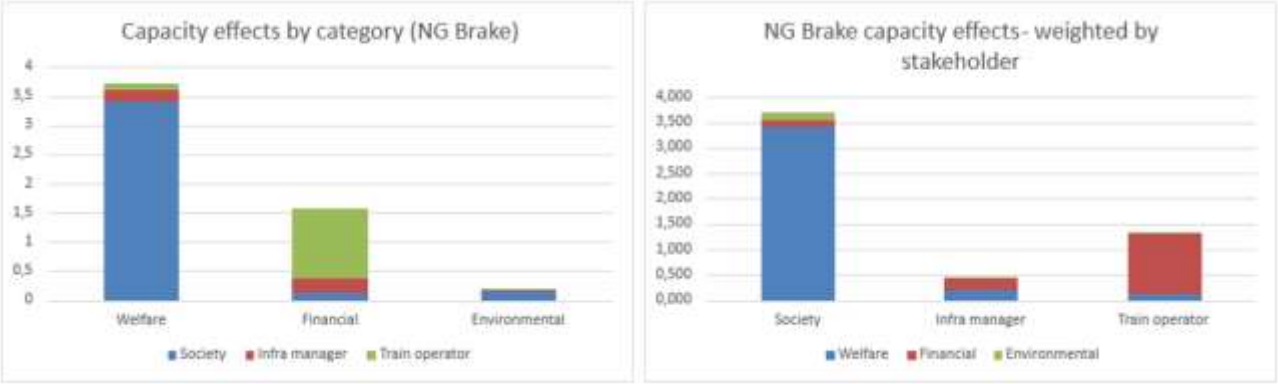


Figure 44: Semi-quantitative value mapping by effect category and stakeholder (NG Brake)

7.2.3.2 Sweden

The NG brake scenarios were only simulated on the line Stockholm-Linköping (East Link) and only the dry scenarios are calculated for value of time, see Table 28 below. There are large uncertainties of how many days there are slippery conditions and on the length of the tracks with slippery conditions. For the NG Brake scenario, the value of time is equal between reduced travel time and reduced delay but the scenario with ATO and NG Brakes it is more beneficial to reduce the travel time than the delays. For all scenarios there are positive value of time by introducing NG Brakes.

Per annum	NG Brakes	ATO and NG Brakes
Value of time - Reduced travel time	EUR 1.43M	EUR 5.85M
Value of time – Reduced delays	EUR 1.43M	EUR 3.23M

Average number of passengers per direction and day	29 000	29 000

Table 28: Benefits of NG Brake (only dry) compared to manual driving without NG Brake

7.3 REFLECTION

Our capacity simulations show quite strong traffic-induced benefits for all three techniques, considering we analyse lines that span fractions of the entire countries' networks, only report yearly estimates and not total life cycle numbers, and still find benefits up to dozens of millions for ATO on the ESAAL corridor.

Regarding our semi-quantitative value mapping, we observed that no matter the technique, the relative story remained similar. While every stakeholder benefits from traffic-change induced effects, society experiences the bulk of these benefits, with more limited roles for the train operator and infra manager. Deliverable 32.1 (van den Berg et al., 2026) shows that these latter stakeholders are the ones that experience the bulk of the costs, at least perceptively. In such, the stakeholder effect decomposition can be a valuable resource to encourage resource redistribution across stakeholders to expedite implementation projects.

From our semi-quantitative value dimension scores per DATO technique, we can also compare effects across techniques using global weights. Figure 45 below shows this. We see that ATO is most beneficial, while NG Brake and HTD have much lower total effect sizes. Nonetheless, if one construes NG Brake as a prerequisite for running an ATO GoA2 timetable with lower running time allowance and headway allowance to prevent total failure in low adhesion conditions, then NG Brake remains relatively interesting. Similarly, if HTD leads to a strong reduction in operational costs through savings on axle counters, and the train operator does not incur proportional extra costs from installing train integrity modules, then it too remains strongly recommended for fast and total roll-out.

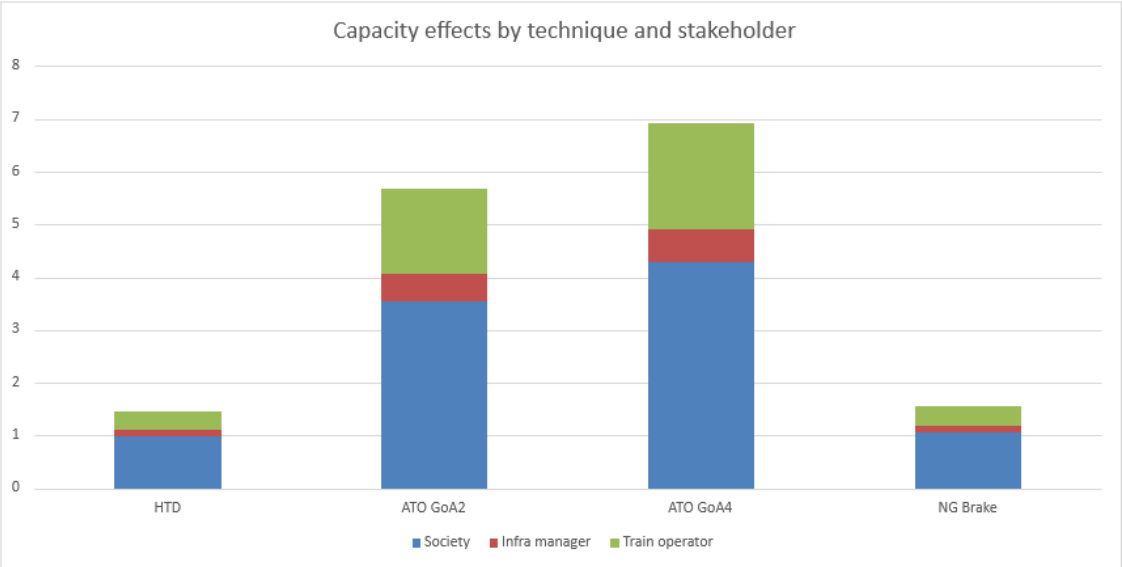


Figure 45: Semi-quantitative value mapping by technique and stakeholder

8 CONCLUSIONS

This Deliverable explored how Digital and Automated up to Autonomous Train Operation (DATO) techniques affect railway capacity and how such effects can be translated into economic and financial outcomes.

The primary contribution was to construct and apply a structured framework in the form of an interface matrix that links simulated changes in the spatio-temporal behaviour of trains to economic and financial value indicators. The interface matrix is not limited to DATO and can serve as a generic reference for assessing any intervention that alters the spatio-temporal behaviour of trains.

Specifically, the model aggregates capacity effects from ten capacity building blocks into four capacity indicators and subsequently translates these into fourteen Business Case (BuCa) value indicators through a defined set of intermediate steps. By explicitly identifying endogenous variables, the matrix highlights that DATO technologies do not only generate capacity effects but may also change the constraints under which capacity is allocated.

Next, the deliverable developed DATO-specific interface matrices for a broad range of technologies, including C-DAS, ATO, HTD, NG Brake, TMS, and DAC/FDFT. These tailored matrices clarify how and where each technique affects capacity, and which economic channels these changes may activate.

The second contribution of this Deliverable was to apply our interface matrix to real capacity simulation outputs from FP1-WP9 for five use cases in the Netherlands and Sweden. Using both quantitative indicators and semi-quantitative value mapping, the deliverable demonstrated how simulation results can be translated into indicative economic and financial impacts, thereby illustrating the practical applicability of the interface matrix as well as offering a well-founded insight into the capacity impacts of ATO, HTD and NG Brake.

Across the studied use cases, the application of the interface matrix shows that DATO techniques can generate substantial traffic-induced benefits. These benefits arise primarily through improved operational stability and reduced running and stopping times. The results consistently indicate that the largest share of value accrues to society, driven by passenger time savings, operational stability improvements, induced demand, agglomeration effects, and welfare gains from modal shifts. Train operators also benefit, mainly through increased ticket revenues and improved asset utilization, while infrastructure managers experience comparatively smaller positive impacts from traffic-induced effects alone.

Among the evaluated technologies, ATO (both GoA2 and GoA4) shows the largest and most robust impact across contexts, followed by NG Brake, which proves particularly valuable in mitigating performance degradation under adverse adhesion conditions. HTD demonstrates strong potential to improve operational stability and to reduce the need for trackside detection assets, while offering capacity benefits where shorter virtual blocks are feasible.

At the same time, the analysis reinforces the existence of trade-offs inherent to capacity planning. Reductions in allowance times, for example, can increase throughput or reduce travel times, but may reduce operational stability if not compensated elsewhere. The interface matrix makes these trade-offs explicit and therefore enables more informed policy and design choices.

We signal several limitations. First, the economic valuation remains partial due to limited human and data resources we had available during this project. Specifically, many BuCa value indicators require

detailed cost, revenue, or demand data from stakeholders that were not available within the scope of this deliverable. Consequently, the application focused on a subset of indicators and relies partly on semi-quantitative assessment.

Second, results are sensitive to reference scenario assumptions, particularly regarding driver behaviour and allowance norms. This was especially evident in the Swedish cases, where uncertainty around manual driving performance affects and likely leads to an understatement of the benefits of ATO and NG Brake.

Third, the framework captures traffic-induced effects only. We deliberately excluded direct costs and benefits of technology implementation, such as investment, maintenance, and human factors effects, as these fall within the scope of the broader Business Case methodology of Deliverable 32.1 (van den Berg et al., 2026) instead.

A key lesson is that capacity benefits should not be treated as fixed outcomes of a technology, but as effects that are allocated by design choices. Timetable design, allowance strategy, and stakeholder objectives strongly influence where and how the benefits ultimately materialise.

Consequently, future research can focus on improved parameterisation, more advanced simulation models, and incorporation of the time dimension through migration scenarios in conjunction with a life cycle costing and future DATO pathway analysis. In addition, future capacity simulations may aim to design integrated network-level timetables that cash in the running time benefits for ATO.

The results of this deliverable underline that DATO technologies can play a significant role in improving the capacity and cost-efficiency of the European railway system. By offering a transparent link between capacity simulations and economic appraisal, this work supports evidence-based prioritisation of technologies within Europe's Rail.

Future activities within Europe's Rail could build on this framework by applying it in project selection and investment appraisal. Indeed, chapter 3 suggests many performance indicators, both at the technical level to measure capacity building blocks and capacity indicators, as well as at the economic and financial level.

In conclusion, this deliverable demonstrates both why DATO capacity effects matter and how they can be translated into meaningful economic and financial insights. It thereby strengthens the analytical foundation for accelerating digital and automated railway innovations in Europe.

REFERENCES

Albrecht, A., Howlett, P., Pudney, P., Vu, X., & Zhou, P. (2016). The key principles of optimal train control—Part 1: Formulation of the model, strategies of optimal type, evolutionary lines, location of optimal switching points. *Transportation Research Part B: Methodological, 94*, 482–508. https://doi.org/10.1016/j.trb.2015.07.023

Albrecht, A. R., Howlett, P. G., Pudney, P. J., Vu, X., & Zhou, P. (2016b). The key principles of optimal train control—Part 2: Existence of an optimal strategy, the local energy minimization principle, uniqueness, computational techniques. *Transportation Research Part B: Methodological*. https://doi.org/10.1016/j.trb.2015.07.024

Andersson, E., Berg, M., Stichel, S., & Casanueva, C. (2018). *Rail systems and rail vehicles: Part 1—Rail systems*. KTH Royal Institute of Technology.

Aoun, J., Knutsen, D., Looij, P., Martinez Sierra, A., Pieters, J., Reyes, J.A. (2026a). *Deliverable 37.2 – Methodology for optimised placement of (virtual) blocks*. Europe's Rail FP2-R2DATO.

Aoun, J., Arachtingi, A., van den Berg, T., Knutsen, D., Looij, P., López González, Á., Martinez Sierra, A., Pieters, J., & Pot, A. (2026b). *Deliverable 37.4 – Determining ETCS HTD/HL3 capacity impact analysis using simulations.* Europe's Rail FP2-R2DATO.

AŽD. (2024). Automatic train operation and ETCS. https://www.azd.cz/en/other-information/system-solution

van den Berg, T., Barbieri, G., Kusumastuti, S., Morin, X., Mowlaei, Z., Solera Jimenez, M., Olsson, N., & van Pelt, R. (2026). *Deliverable 32.1 – DATO Business Case*. Europe's Rail FP2-R2DATO.

Betts, J. T. (2010). *Practical methods for optimal control and estimation using nonlinear programming* (2nd ed.). SIAM. https://doi.org/10.1137/1.9780898718577

Bienfait, B. (2017). *ATO/DAS over ETCS: The way towards unattended operation for Main Lines*.

Corlu, C. G., de la Torre, R., Serrano-Hernandez, A., Juan, A. A., & Faulin, J. (2020). *Optimizing energy consumption in transportation: Literature review, insights, and research opportunities*. Energies, 13(5), 1115. https://doi.org/10.3390/en13051115

Donaldson, D., & Hornbeck, R. (2016). *Railroads and American economic growth: A market access approach.* The Quarterly Journal of Economics, 131(2), 799–858. https://doi.org/10.1093/qje/qjw002

van Essen, H., Van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., & El Beyrouty, K. (2019). *Handbook on the external costs of transport: Version 2019* (Publication No. 18.4 K83.131). Publications Office of the European Union. https://doi.org/10.2832/27212

European Commission. (2014). *Guide to cost-benefit analysis of investment projects: Economic appraisal tool for cohesion policy 2014–2020*. Publications Office of the European Union. https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf

European Environment Agency. (2021). *Rail and waterborne transport — best for low-carbon motorised transport* (EEA Report No. TH-AM-21-001-EN-Q). Publications Office of the European Union. https://doi.org/10.2800/817894

European Parliament and Council. (2012). *Directive 2012/34/EU of the European Parliament and of the Council of 21 November 2012 establishing a single European railway area (recast).* Official Journal of the European Union, L 343, 32–77. https://eur-lex.europa.eu/eli/dir/2012/34/oj

European Union Agency for Railways. (2020). *SUBSET-026: System requirements specification (ETCS baseline 3 release 2, version 3.6.0).*

European Union Agency for Railways. (2024). *Report on railway safety and interoperability in the EU 2024*. Publications Office of the European Union. https://doi.org/10.2821/64343

Förstberg, J. (2000). *Ride comfort and motion sickness in tilting trains* (Doctoral dissertation, KTH Royal Institute of Technology). https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-2985

Fosgerau, M. (2016). *The valuation of travel time variability* (International Transport Forum Discussion Paper No. 2016-04). Organisation for Economic Co-operation and Development (OECD), International Transport Forum. https://hdl.handle.net/10419/173911

Gattuso, D., & Restuccia, A. (2014). A tool for railway transport cost evaluation. *Procedia - Social and Behavioral Sciences, 111*, 549–558. https://doi.org/10.1016/j.sbspro.2014.01.087

Geurs, K. T., Boon, W. P. C., & van Wee, B. (2009). Social impacts of transport: Literature review and the state of the practice of transport appraisal. *Transport Reviews, 29*(1), 69–90. https://doi.org/10.1080/01441640802130490

Goverde, R. M. P., & Hansen, I. A. (2013). *Performance indicators for railway timetables*. In *Proceedings of the 2013 IEEE International Conference on Intelligent Rail Transportation* (pp. 301–306). IEEE. https://doi.org/10.1109/ICIRT.2013.6696312

Goverde, R. M. P., Scheepmaker, G. M., & Wang, P. (2021). Pseudospectral optimal train control. *European Journal of Operational Research, 292*(1), 353–375. https://doi.org/10.1016/j.ejor.2020.10.018

Graffagnino, T., Schäfer, R., Tuchschmid, M., & Weibel, M. (2019). Energy savings with enhanced static timetable information for train drivers. In *8th International Conference on Railway Operations Modelling and Analysis (RailNorrköping 2019)*, Linköping Electronic Conference Proceedings, 69:23, 340–349. https://ep.liu.se/ecp/069/023/ecp19069023.pdf

van Hagen, M., & de Bruyn, M. (2015). *Emotions during a train-journey quantified.* Paper presented at the European Transport Conference, Frankfurt, Germany. https://aetransport.org/public/downloads/1oA8x/4567-55e2dd43773af.pdf

Hansen, I. A., & Pachl, J. (Eds.). (2014). *Railway timetabling & operations: Analysis, modelling, optimisation, simulation, performance evaluation* (2nd ed.). Eurailpress. ISBN 978-3-7771-0462-1.

Hansen, W. G. (1959). *How accessibility shapes land use.* Journal of the American Institute of Planners, 25(2), 73–76. https://doi.org/10.1080/01944365908978307

Hansson, J., Pettersson-Löfstedt, F., Svensson, H., & Wretstrand, A. (2022). Effects of rural bus stops on travel time and reliability. *Public Transport, 14*, 683–704. https://doi.org/10.1007/s12469-021-00281-1

Hé, J., & Li, Z. (2025). *Deliverable 32.3 – ATO Impact on Infra-Structure Assessment Analysis Report.* Europe's Rail FP2-R2DATO.

Howlett, P. G., & Pudney, P. J. (1995). *Energy-efficient train control* (Advances in Industrial Control). https://doi.org/10.1007/978-1-4471-3084-0

de Jong, G. (2018). Determining price elasticities of rail transport demand for market-can-bear tests. Paper presented at the *European Transport Conference*, Frankfurt, Germany. https://significance.nl/wp-content/uploads/2019/04/2018-GDJ-Determining-price-elasticities-of-rail-demand-for-market-can-bear-tests.pdf

de Jong, M. P., & ter Horst, D., *Energiebesparing door gebruik RTA tot en met juli 2019,* 2019, Report, NS.

de Jong, G., & Kouwenhoven, M. (2020). Value of travel time and travel time reliability. In *Advances in Transport Policy and Planning* (Vol. 6, pp. 43–74). https://doi.org/10.1016/bs.atpp.2020.01.003

de Jong, G., & Fare, B. (2021). Quantifying travellers' evaluation of waiting time uncertainty in public transport networks. *Transportation Research Part A: Policy and Practice, 148*, 264–280. https://doi.org/10.1016/j.tra.2021.07.015

Kent, S. (2009). *Driver advisory information for energy management and regulation: Stage 1 report – appendices* (Technical Report). DeltaRail.

Kouwenhoven, M., & de Jong, G. (2018). Value of travel time as a function of comfort. *Journal of Choice Modelling, 28*, 97–107. https://doi.org/10.1016/j.jocm.2018.05.002

Kouwenhoven, M., Muller, J., Thoen, S., Willigers, J., & De Jong, G. (2023). *Values of time, reliability and comfort in the Netherlands 2022. New values for passenger travel and freight transport*. Netherlands Institute for Transport Policy Analysis (KiM). https://english.kimnet.nl/site/binaries/site-content/collections/documents/2024/04/03/new-values-of-travel-time-reliability-and-comfort-in-the-netherlands/Technical+report+Significance_+Values+of+Travel+Time+in+the+Netherlands+2022_final.pdf

Kroes, E., & Koopmans, C. (2014). The value of comfort. In P. Warffemius, M. van Hagen, M. de Bruyn, P. Bakker, & J. van der Waard, *The value of comfort in train appraisal.* The Hague, Netherlands: Netherlands Institute for Transport Policy Analysis (KiM).

Krugman, P. (1991). *Increasing returns and economic geography.* Journal of Political Economy, 99(3), 483–499. https://doi.org/10.1086/261763

Lo, J., Borsci, S., Dressler, A., Holmgren, M., Kolkman, T., & Kusumastuti, S. (2026). *Deliverable 32.4 – ATO Human Factors Impact Assessment Analysis Report*. Europe's Rail FP2-R2DATO.

Luijt, R. S., van den Berge, M. P. F., Willeboordse, H. Y., & Hoogenraad, J. H. (2017). 5 years of Dutch eco-driving: Managing behavioural change. *Transportation Research Part A: Policy and Practice, 98*, 46–63. https://doi.org/10.1016/j.tra.2017.01.019

Mackie, P. J., Jara-Díaz, S., & Fowkes, A. S. (2001). The value of travel time savings in evaluation. *Transportation Research Part E: Logistics and Transportation Review, 37*(2–3), 91–106. https://doi.org/10.1016/S1366-5545(00)00015-6

Marshall, A. (1920). *Principles of economics* (8th ed.). Macmillan. http://www.econlib.org/library/Marshall/marP.html

Meijeren, J., & van de Lande, P. (2020). *ATO, gamechanger voor de toekomst van het spoor: Positionpaper Automatic Train Operation*. TNO. https://publications.tno.nl/publication/34637578/LC3k3H/TNO-2020-ato.pdf

Mohring, H. (1972). Optimization and scale economies in urban bus transportation. *The American Economic Review, 62*(4), 591–604. https://www.jstor.org/stable/1806101

Nolte, J. (2021). *ATO2Basic Phase 2 Final Report (Version 1.0)*. https://www.voev.ch/de/Service/content_?download=18098

van Oort, N. (2011). *Service reliability and urban public transport design* (Doctoral thesis). Delft University of Technology. https://resolver.tudelft.nl/uuid:68f6dd34-53cf-4792-81e7-799c3d552b94

Peftitsi, S., Jenelius, E., & Cats, O. (2023). Evaluating skip-stop policy in urban rail transit systems based on passenger cost. *Journal of Public Transportation, 25*, 100064. https://doi.org/10.1016/j.jpubtr.2023.100064

Polydoropoulou, A., & Yai, T. (2008). Waiting time and the role and value of information in scheduled transport. *Research in Transportation Economics, 23*(1), 41–52. https://doi.org/10.1016/j.retrec.2008.10.005

Pontryagin, L. S., Boltyanskii, V. G., Gamkrelidze, R. V., & Mishchenko, E. F. (1962). *The mathematical theory of optimal processes*. Wiley.

Pot, A., van den Berg, T., Koopman – van Welij, D., Arachtingi, A., Andres Martinez, M., Ramos Prieto, C., Meseguer Hijós, I., Ciáurriz, P., Díez de Ulzurrun, U., Jansson, E., Sipilä, H., Lindfeldt, A., Knutsen, D., Olsson, N., & Rosberg, T. (2025). *Deliverable D 8.3 – Developed simulation methods and models for capacity evaluation of ETCS and C-DAS/ATO.* Europe's Rail FP1-MOTIONAL. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e522ec7515&appId=PPGMS

Rao, A. V. (2014). Trajectory optimization: A survey. In H. Waschl, I. Kolmanovsky, M. Steinbuch, & L. del Re (Eds.), *Optimization and optimal control in automotive systems* (pp. 3–21). Springer. https://doi.org/10.1007/978-3-319-05371-4

Ritsema van Eck, J., Hof, B., & 't Hoen, M. (2025). *Toekomstverkenning WLO: Vier scenario's voor Nederland in 2040, 2050 en 2060* (PBL-publicatienummer 5450). Planbureau voor de Leefomgeving. https://www.wlo2025.nl/downloads/pbl-2025-toekomstverkenning-wlo-vier-scenarios-5450pdf

Rojas, A., Palmqvist, C. W., & Camporeale, R. (2026). *The socioeconomic impact of train stations: Evidence from a 20-year study in Sweden.* Transportation Research Part A: Policy and Practice, 204, 104826. https://doi.org/10.1016/j.tra.2025.104826

Rubel, F. (2024). *DAS at DB Fernverkehr. History, measuring concept and current development.*

Scheepmaker, G. M., & Goverde, R. M. P. (2015). The interplay between energy-efficient train control and scheduled running time supplements. *Journal of Rail Transport Planning & Management, 5*(4), 225–239. https://doi.org/10.1016/j.jrtpm.2015.10.003

Scheepmaker, G. M., Pudney, P. J., Albrecht, A. R., Goverde, R. M. P., & Howlett, P. G. (2020a). Optimal running time supplement distribution in train schedules for energy-efficient train control. *Journal of Rail Transport Planning & Management, 14*, Article 100180. https://doi.org/10.1016/j.jrtpm.2020.100180

Scheepmaker, G. M., Willeboordse, H. Y., Hoogenraad, J. H., Luijt, R. S., & Goverde, R. M. P. (2020b). Comparing train driving strategies on multiple key performance indicators. *Journal of Rail Transport Planning & Management, 13*, Article 100163. https://doi.org/10.1016/j.jrtpm.2019.100163

Shift2Rail. (2021). *DAC-Factsheet*. https://rail-research.europa.eu/wp-content/uploads/2021/04/DAC-Factsheet_EN.pdf

Siemens. (2024). *ATO over ETCS*. https://www.mobility.siemens.com/global/en/portfolio/digital-solutions-software/infrastructure/ato-over-etcs.html

Small, K. A., & Verhoef, E. T. (2007). *The economics of urban transportation.* London, United Kingdom: Routledge. https://doi.org/10.4324/9781315157375

Smith, A., Iwnicki, S., Kaushal, A., Odolinski, K., & Wheat, P. (2017). Estimating the relative cost of track damage mechanisms: Combining economic and engineering approaches. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 231*(6), 620–636. https://doi.org/10.1177/095440971769885

Su, S., Tian, Z., & Goverde, R. M. P. (2023). *Energy-efficient train operation: A system approach for railway networks*. Springer. https://doi.org/10.1007/978-3-031-34656-9

Trafikverket. (2022). *Elasticiteter I Sampers 4*. https://bransch.trafikverket.se/contentassets/ef39a7c8e2964def82ee114d4d3798b5/2024/elasticiteter-i-sampers-4-2022-11-24.pdf

Trafikverket. (2024). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn (ASEK 8.0)* (Report, 2 April 2024). https://bransch.trafikverket.se/contentassets/0e5777a6301e4134a6e8365fc20c0e0e/asek-8.0-2-april-2024.pdf

UIC [International Union of Railways]. (2013). *UIC 406: Capacity* (2nd ed., Leaflet). UIC.

UIC [International Union of Railways]. (2000). *UIC Leaflet 451-1: Braking – Braking performance* (4th ed.). UIC.

Wardman, M. (2004). Public transport values of time. *Transport Policy, 11*(4), 363–377. https://doi.org/10.1016/j.tranpol.2004.05.001

Wardman, M., & Whelan, G. (2011). Twenty years of rail crowding valuation studies: Evidence and lessons from British experience. *Transport Reviews, 31*(3), 379–398. https://doi.org/10.1080/01441647.2010.519127

Wardman, M., Chintakayala, V. P. K., & de Jong, G. (2016). *Values of travel time in Europe: Review and meta-analysis*. *Transportation Research Part A: Policy and Practice, 94*, 93–111. https://doi.org/10.1016/j.tra.2016.08.019

Warffemius, P., van Hagen, M., de Bruyn, M., Bakker, P., & van der Waard, J. (2016). *The value of comfort in train appraisal.* Netherlands Institute for Transport Policy Analysis (KiM). https://english.kimnet.nl/site/binaries/site-content/collections/documents/2016/10/5/the-value-of-comfort-in-train-appraisal-kopie/The+value+of+comfort+in+train+appraisal.pdf

Warffemius, P. (2015). *Effecten van veranderingen in reistijd en daaraan gerelateerde kwaliteitsaspecten in het openbaar vervoer.* Netherlands Institute for Transport Policy Analysis (KiM). https://www.kimnet.nl/site/binaries/site-content/collections/documents/2015/11/5/effecten-van-verandering-in-reistijd-en-daaraan-gerelateerde-kwaliteitsaspecten-in-het-openbaar-vervoer/effecten-van-verandering-in-reistijd-en-daaraan-gerelateerde-kwaliteitsaspecten-in-het-openbaar-vervoer.pdf

APPENDIX A: ANALYTICAL STUDY OF ENERGY EFFICIENCY

A1 Background and methods

This appendix presents an analytical study into the four different driving strategies outlined in Section 3.3.4.1. Specifically, the study calculates actual potential energy consumption decreases associated with them as one moves from MTTC to RMS, then MC, then EETC, for one popular short-distance and one popular long-distance train type used by the Dutch railways (NS).

The driving strategy has a large impact on the energy consumption of a train. The train driver or ATO (automatic train operation) system can apply different driving strategies (see Figure 46 below) to minimize the energy consumption and to run on-time (i.e., not too early and not too late) using the running time allowances in the timetable. These allowances are the extra running time on top of the technical minimum running time in the timetable to cope with running time variations and to recover from small delays (Scheepmaker & Goverde, 2015). However, if a train runs on-time, these allowances can be used to apply energy-efficient train driving or eco-driving. In this section we will discuss four different driving strategies, i.e., minimum time train control (MTTC), maximum coasting (MC), reduced maximum speed (RMS), energy-efficient train control (EETC) (Scheepmaker et al., 2020b). The MTTC driving strategy aims to minimize the total running time and is not an eco-driving strategy, while the other driving strategies are. This section starts with the assumptions that sufficient running times allowances are available in the timetable to apply energy-efficient train driving, the focus is on a single train, and that the train applies mechanical braking only. During mechanical braking the braking disks or pads are used to convert kinetic energy into heat.

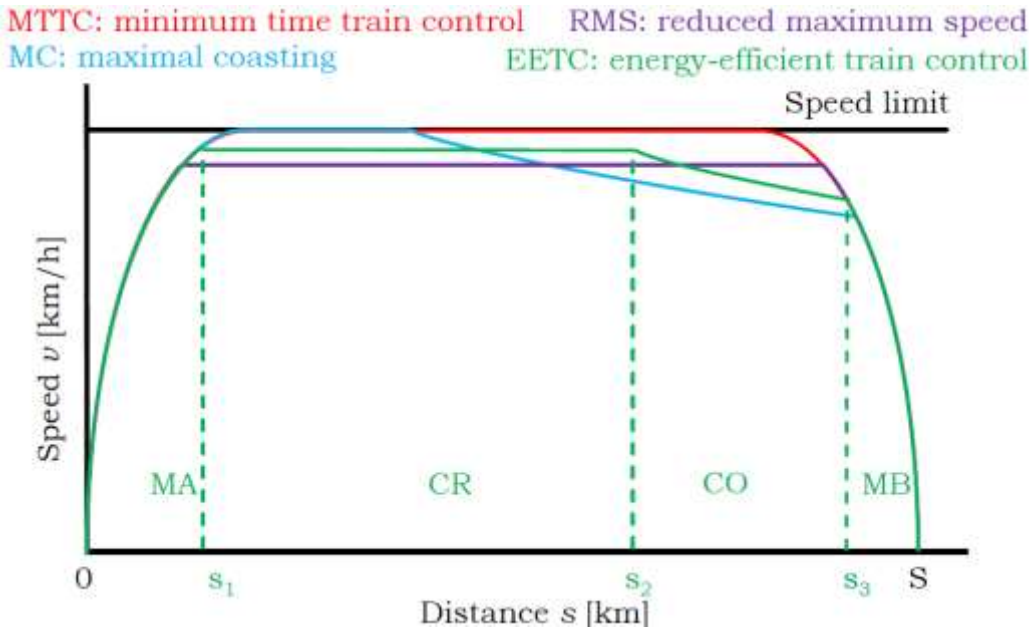


Figure 46: Speed-Distance diagram of different (energy-efficient) driving strategies

Note: speed-distance profiles for a simple flat track without varying speed limits. MA = maximum acceleration, CR = cruising, CO = coasting and MB = maximum braking. Driving strategies switch the location of s_1, s_2, and s_3)

The first driving strategy that will be described is the MTTC or technical minimum running time driving strategy. In this driving strategy, the train runs as fast as possible by the driving regimes maximum acceleration (MA), cruising (CR) or speed-holding at the speed limit and maximum braking (MB) (see Figure 46 above). This driving strategy is applied in practice in case of delays. In addition, the MTTC driving strategy is also used during timetable design to determine the amount and distribution of running time allowances. Next, three eco-driving strategies are discussed.

The first eco-driving strategy is the reduced maximum speed driving strategy, which is based on applying cruise control (speed-holding). The train applies the driving regimes MA, CR or speed-holding below the speed limit, and MB (see Figure 46 above). The challenge for this driving strategy is to determine the optimal cruising speed. This driving strategy is for instance applied at the Swiss Federal Railways (SBB) (Graffagnino et al., 2019).

The second eco-driving strategy is focused on coasting and is called the maximum coasting driving strategy (see Figure 46 above). In this case the driving regimes MA, CR at the speed limit, coasting (CO) and MB are applied. However, for short distances the driving regime CR at the speed limit is omitted and the train directly starts to coast after MA. The main challenge for this driving strategy is to determine the starting point for coasting. This driving strategy is for instance applied at the Netherlands Railways (NS) (Scheepmaker & Goverde, 2015; Luijt et al., 2017).

The last eco-driving strategy is the energy-efficient train control or the energy-optimal driving strategy. In this case the train applies the driving regimes MA, CR below the speed limit, CO and MB (see Figure 46 above). However, for short distances between stops the EETC driving strategy is the same as the MC driving strategy (Scheepmaker et al., 2020b). The challenge of this driving strategy is to compute both the optimal cruising speed and starting point for coasting. Therefore, this EETC driving strategy might be difficult to apply by a train driver real-time without any digital support system, so therefore, this driving strategy is more suitable for a driver advisory system (DAS) or even better by an ATO system (human out of the loop). Note that for all eco-driving strategies the train applies maximum acceleration and maximum braking, due to the high traction efficiency, the heavy weight and the low rolling resistance of trains. More details on those four driving strategies can be found in Scheepmaker, et al. (2020b).

A lot of research focuses on determining the EETC driving strategy, because this leads to the lowest traction energy consumption of a train (Scheepmaker et al., 2017). The EETC driving strategy can be determined using optimal control theory. First, the optimal control problem is formulated. Afterwards, the Hamiltonian and augmented Hamiltonian function and the costate variables are defined. Then Pontryagin's Maximum Principle (PMP) is applied to derive the optimal driving regimes and the necessary optimality conditions (Pontryagin et al., 1962). Basically, the optimal control structure consists of the driving regimes MA, CR, CO, and MB and the switching points between those regimes are determined by the value of one of the costate values. An example of the EETC driving strategy on a simple scenario consisting of flat track and without varying speed limits, and sufficient running time allowances can be found in Figure 46 above. More details regarding the optimal control problem formulation and the exact derivation of the optimality conditions can be found in Howlett & Pudney (1995), Albrecht et al. (2016a, b), Scheepmaker et al. (2017), Goverde et al. (2021), and Su et al. (2023).

The EETC driving strategy becomes more difficult to determine when for instance varying speed limits, varying gradients, critical intermediate timing points[2] and regenerative braking[3] are included. Therefore, there are different methods to solve the EETC problem in practice: indirect solution methods, direct solution methods, and heuristics (Betts, 2010; Rao, 2014; Scheepmaker et al., 2017). First, indirect solution methods can be applied that derive the optimal control structure using PMP, which leads to a two-point boundary problem, thus makes it an indirect solution method to solve the original optimal control problem. Constructive algorithms are applied that use the knowledge of the optimal control structure to solve the problem efficiently. Second, direct solution methods can be used that translate the optimal control problem to a nonlinear programming (NLP) problem and solve it using NLP solvers. They do not need information about the optimal control structure as input to solve the problem (Rao, 2014). Finally, heuristics can be used to determine the EETC, although heuristics do not provide insights whether the global optimal solution is found.

Energy savings of using a C-DAS or an ATO can be significant. However, comparing the energy savings might be difficult, because they depend for instance on the reference scenario, the length of the trajectory, the rolling stock characteristics, and the amount and distribution of the running time allowances. In addition, the application of ATO GoA 2 or 4 in practice for heavy rail is very limited. Albrecht et al. (2016a) report energy savings up to 20% by using the C-DAS called Energymiser, which is for instance used at SNCF. SBB achieved energy savings by their vPRO driver advisory system (compared to train drivers without the advice) varying between 7% to 14% for regional trains and 1% to 8% for long distance trains (Graffagnino et al., 2019). DB Fernverkehr applies digital timetable EBuLa-ESF with coasting advice since 2002, where energy savings of about 5% where achieved (Kent, 2008). In 2018 DB InfraGo added ZLR (C-DAS) in the digital timetable that computes the speed advice (cruising and coasting) based on input from the TMS regarding critical timetable points where there is interaction with other trains. The aim is to avoid potential conflicts between trains and to decrease the traction energy consumption. Energy savings by ZLR where about 0.2% in 2023 (Rubel, 2024). NS implemented a C-DAS (*TimTim Pro*) in 2019, utilizing the maximum coasting strategy. This has resulted in approximately 6% gains in energy efficiency compared to driving without a C-DAS (de Jong & ter Horst, 2019).

However, measuring the impact of the implementation of C-DAS or ATO on energy consumption does not tell the whole story, as it also depends on the extent to which drivers were already practicing energy-efficient driving techniques. In a 2017 presentation, train supplier Alstom illustrated that ATO GoA2 could save up to 42% on regional routes with frequent stops and up to 15% for intercity trains (Bienfait, 2017). In two test runs conducted with ATO GoA2 by SBB, energy savings of 25% and 37% were observed, respectively (Nolte, 2021). SBB concluded that Alstom's estimates of energy savings exceeding 40% should be considered realistic. Additionally, the application of ATO GoA2 in the Czech Republic under conventional signalling has reported energy savings of 30% to 40% (Meijeren & van de Lande, 2020). These examples illustrate that the anticipated energy savings from C-DAS and ATO GoA2 vary considerably and that analyses conducted under controlled conditions provide valuable new insights. The percentage reduction is dependent on both actual and estimated performance, but also on the used reference. This means that operators who have had less

[2] Critical timing points are locations where there is interaction with other trains, e.g., switching areas. At these locations the timetable can provide a specific passing time to avoid conflicts between two interacting trains.

[3] During regenerative braking the train uses the engine as a generator to gain energy (electricity). This energy can be used by the train itself (e.g., energy storage in batteries, heating/cooling, lighting) or it can be fed back to the catenary system to supply surrounding trains with energy or energy storage at the trackside.

emphasis on energy efficiency are expected to show higher relative energy reduction, compared to those who have had some policy focused on energy efficiency already (such as training of train drivers).

Previous research focused on determining the EETC driving strategy (Scheepmaker et al., 2017) or comparing different driving strategies on different KPIs (Scheepmaker, et al, 2020b). However, the effect of driving strategies in relation to C-DAS and ATO was not considered. In addition, ATO suppliers claim high energy savings that can be achieved with ATO, e.g., up to 30% (AŽD, 2024; Siemens, 2024). However, the energy savings depend on the reference considered for the ATO. For instance, NS already has the MC driving strategy where significant energy savings can be achieved. The main question is what are the extra energy savings that can be achieved using ATO compared to the current situation with or without C-DAS.

To this end, this analytical study uses the single-phase Radau pseudospectral method to compute the different driving strategies (Scheepmaker et al, 2020b). In this method, the optimal control problem is discretised at the state and control variables using orthogonal collocation at Legendre-Gauss-Radau points. In this way, the optimal control problem is reformulated to a nonlinear programming problem that is solved using NLP solvers (Betts, 2010). For more details regarding the pseudospectral method and the derivation of the optimal control problem, we refer to Goverde et al. (2021). We use the MATLAB toolbox GPOPS version 4.1 to compute the different driving strategies.

A2 Results

This section discusses the results of the different driving strategies applied on different scenarios. We consider the section of about 50 km between the stops Utrecht Central (Ut) and 's-Hertogenbosch (Ht) for a non-stop long distance or Intercity (IC) train and the section of about 12 km between the stops Zaltbommel (Zbm) and Ht for a regional or Sprinter (SPR) train. The IC train consists of a double-deck EMU VIRM with 6 coaches, while the SPR train is a single-deck EMU SLT with 6 coaches. The basic timetable contains 10% running time allowances or running time allowance for both IC and SPR train. We do not consider regenerative braking. In total six different scenarios are considered, and they are shown in Table 29 below. The scenarios consider different variations: the running time allowances, the performance for acceleration and deceleration, varying the speed limits and gradients, and a sensitivity analyses for manual driving (balance MC and RMS). Note that we do not consider regenerative braking (e.g., generate electricity during braking), so during braking the braking discs or braking blocs are applied.

ID	Scenario	Running time allowances	Performance	Driving strategies
1	Reference	0% & 10%	100%	MTTC, MC, RMS & EETC
2	Varying running time allowances	0%, 2.5% 5%, 7.5%, 10%, 12.5% & 15%	100%	MTTC, MC, RMS & EETC
3	Varying performance	10%	50%, 60%, 70%, 80%, 90%, 100%	MTTC, RMS & EETC
4	Varying speed limits	10%	100%	MTTC, MC, RMS & EETC

5	Varying speed limits + gradients	10%	100%	MTTC, MC, RMS & EETC
6	Sensitivity analyses	10%	100%	MC & RMS

Table 29: Scenarios considered for comparison of the different driving strategies

Reference scenario: without varying gradients and speed limits

This scenario considers the reference case without varying the gradients and without varying the speed limits with 10% of running time allowances. First, the results of the IC (InterCity) are discussed followed by the SPR (Sprinter).

Table 30 and Figure 47 below show the results of the reference scenario (without varying gradients and speed limits) for the InterCity (IC). The MTTC driving strategy has the shortest running time, but also the highest energy consumption. In addition, the EETC and MC driving strategy have almost the same energy consumption (difference of about 0.05%), although the speed profile is slightly different. The EETC driving strategy includes a cruising or speed-holding phase lower than the speed limit and a shorter coasting phase compared to the MC driving strategy. Finally, the EETC and MC driving strategy have about 10% lower energy consumption than the RMS driving strategy. Therefore, coasting leads to higher energy savings than cruising for the reference scenario for the IC.

Driving strategy	**Running time [s]**	**Running time allowances**	**Traction energy consumption [kWh]**	**Energy savings compared to MTTC**
MTTC	1331.0	0%	347.1	0%
EETC	1464.1	10%	258.1	-25.6%
MC	1464.1	10%	258.2	-25.6%
RMS	1464.1	10%	287.6	-17.1%

Table 30: Results of the reference scenario IC without varying gradients and speed limits

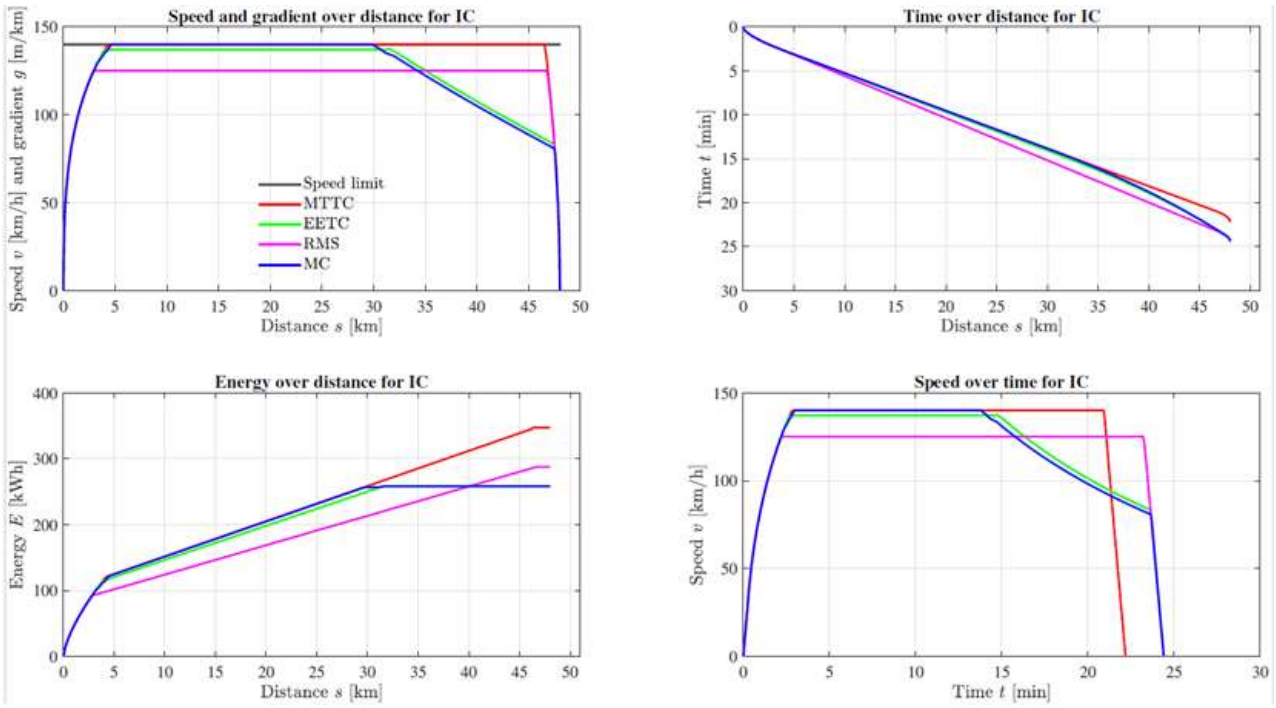


Figure 47: Reference scenario (IC) effects of the different driving strategies

Note: speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), speed-time diagram (bottom right). MTTC = minimum time train control, EETC = energy-efficient train control, MC = maximum coasting, and RMS = reduced maximum speed.

The results for the Sprinter (SPR) regarding the reference scenario (without varying gradients and speed limits) are shown in Table 31 and Figure 48. The results indicate that the MC driving strategy is the same as the EETC driving strategy. In this case, the train accelerates to the maximum speed and directly starts to coast. Energy savings of about 32% can be achieved with the EETC/MC driving strategy compared to MTTC. Furthermore, EETC and MC lead to about 13% higher energy savings compared to RMS. So, also for the SPR reference scenario, coasting leads to higher energy savings than cruising.

Furthermore, the results for the SPR in Table 31 show that the relative energy savings are bigger compared to the IC (see Table 30). This can be explained by the fact that for short distances cruising is missing. Therefore, coasting considers a big part of the total trajectory and earlier coasting directly decreases the maximum speed of the train.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	399.8	0%	83.3	0%
EETC	439.8	10%	56.7	-31.9%
MC	439.8	10%	56.7	-31.9%
RMS	439.8	10%	65.4	-21.5%

Table 31: Results of the reference scenario SPR without varying gradients and speed limits

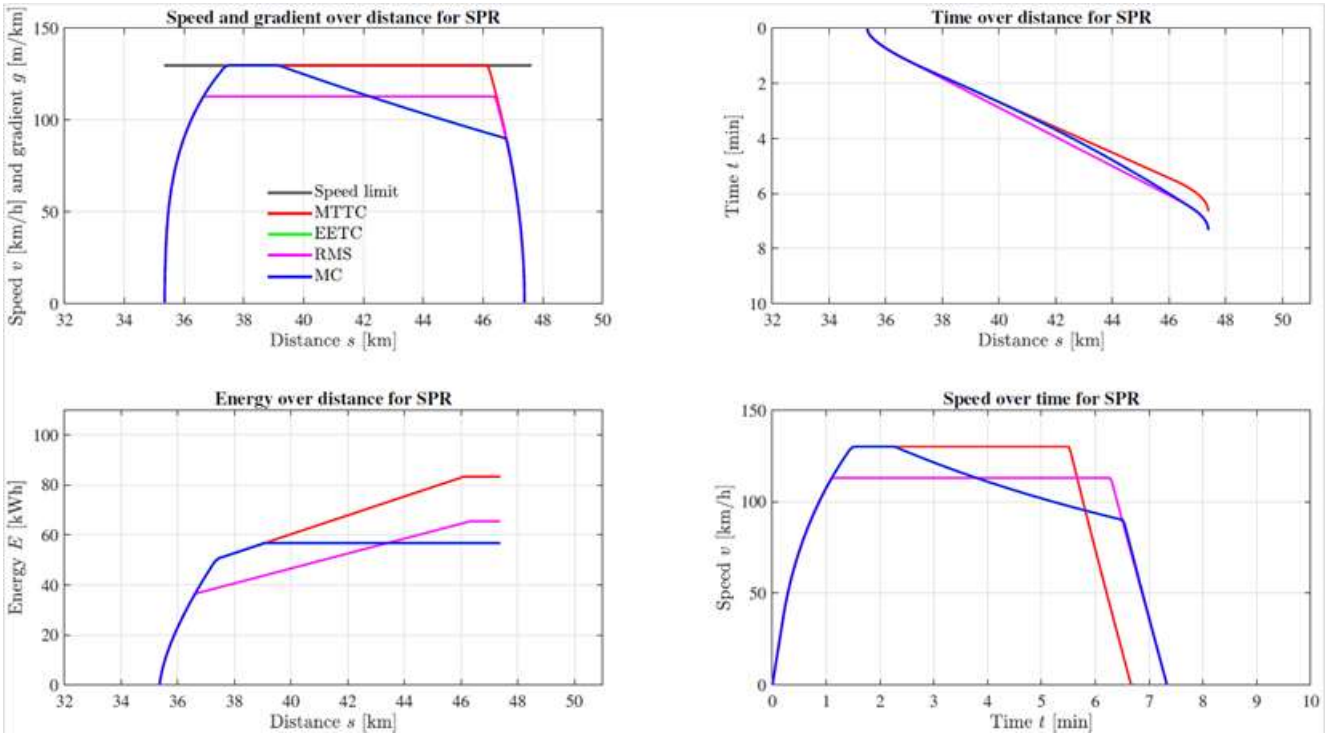


Figure 48: Reference scenario (SPR) effects of the different driving strategies

Note: speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), speed-time diagram (bottom right). MTTC = minimum time train control, EETC = energy-efficient train control, MC = maximum coasting, and RMS = reduced maximum speed.

Scenario: with varying running time allowances

In this scenario we varied the running time allowances from 0% to 15% in steps of 2.5% for the driving strategies EETC, MC and RMS for both IC and SPR. No varying speed limits and gradients are considered here.

The results are shown in Table 32 and Figures 49 and 50 for the IC. The results indicate that the EETC driving strategy is the same as the MC driving strategy when the running time allowances are below 10%. Even for 15% running time allowance, the difference between EETC and MC in energy savings is relatively small (1.6%). The Pareto curve in Figure 50 also shows that relatively the largest energy savings can be achieved when the running time allowances are increased from 0% to 2.5% (steepest gradient of the curve), also known as the diminishing returns curve. Also note that the gradient for the RMS driving strategy is rather constant, while the curve of the MC and EETC driving strategy clearly shows the diminishing returns for higher amounts of running time.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	1331.0	0%	347.1	0%
EETC	1364.3	2.5%	299.2	-13.8%
MC	1364.3	2.5%	299.2	-13.8%

RMS	1364.3	2.5%	329.8	-5.0%
EETC	1397.6	5%	282.5	-18.6%
MC	1397.6	5%	282.5	-18.6%
RMS	1397.6	5%	313.8	-9.6%
EETC	1430.8	7.5%	269.6	-22.3%
MC	1430.8	7.5%	269.6	-22.3%
RMS	1430.8	7.5%	300.2	-13.5%
EETC	1464.1	10%	258.1	-25.6%
MC	1464.1	10%	258.2	-25.6%
RMS	1464.1	10%	287.6	-17.1%
EETC	1497.4	12.5%	247.6	-28.7%
MC	1497.4	12.5%	249.6	-28.1%
RMS	1497.4	12.5%	275.6	-20.6%
EETC	1530.7	15%	237.8	-31.5%
MC	1530.7	15%	241.8	-30.3%
RMS	1530.7	15%	264.8	-23.7%

Table 32: Results of the scenario IC with varying running time allowances

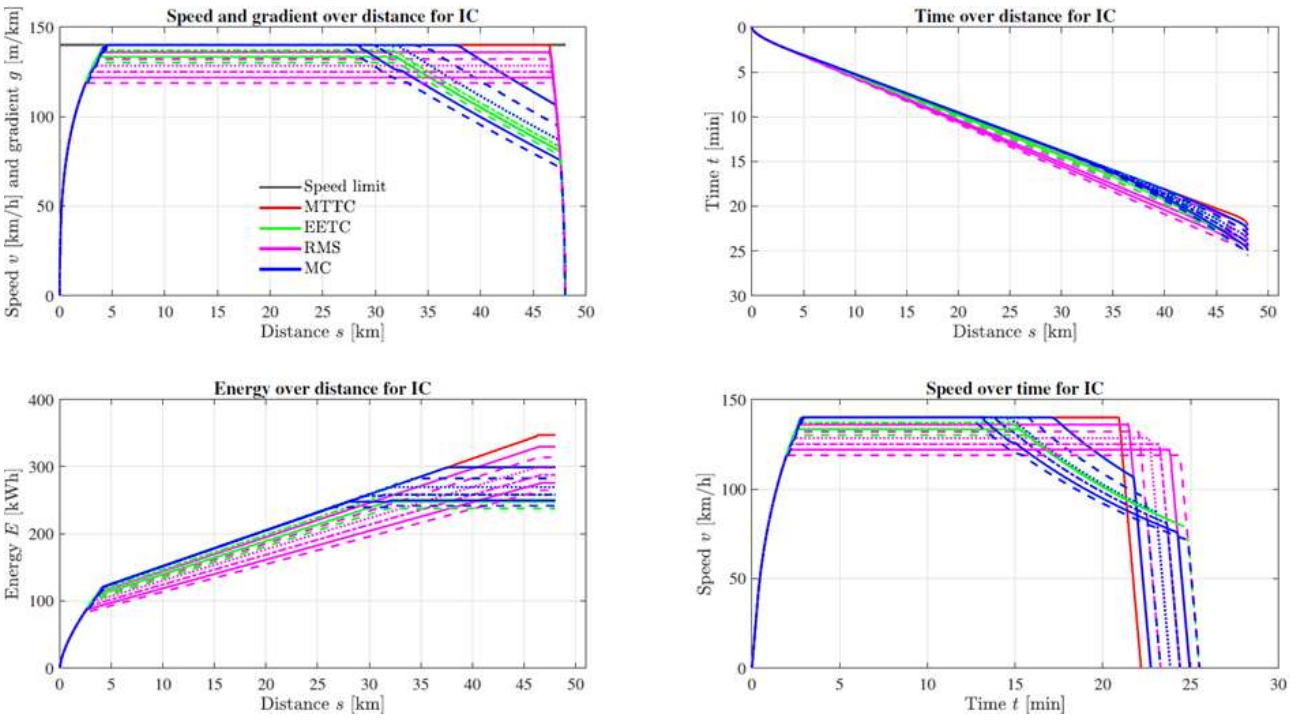


Figure 49: Scenario varying running time allowances (IC) with effects of the different driving strategies

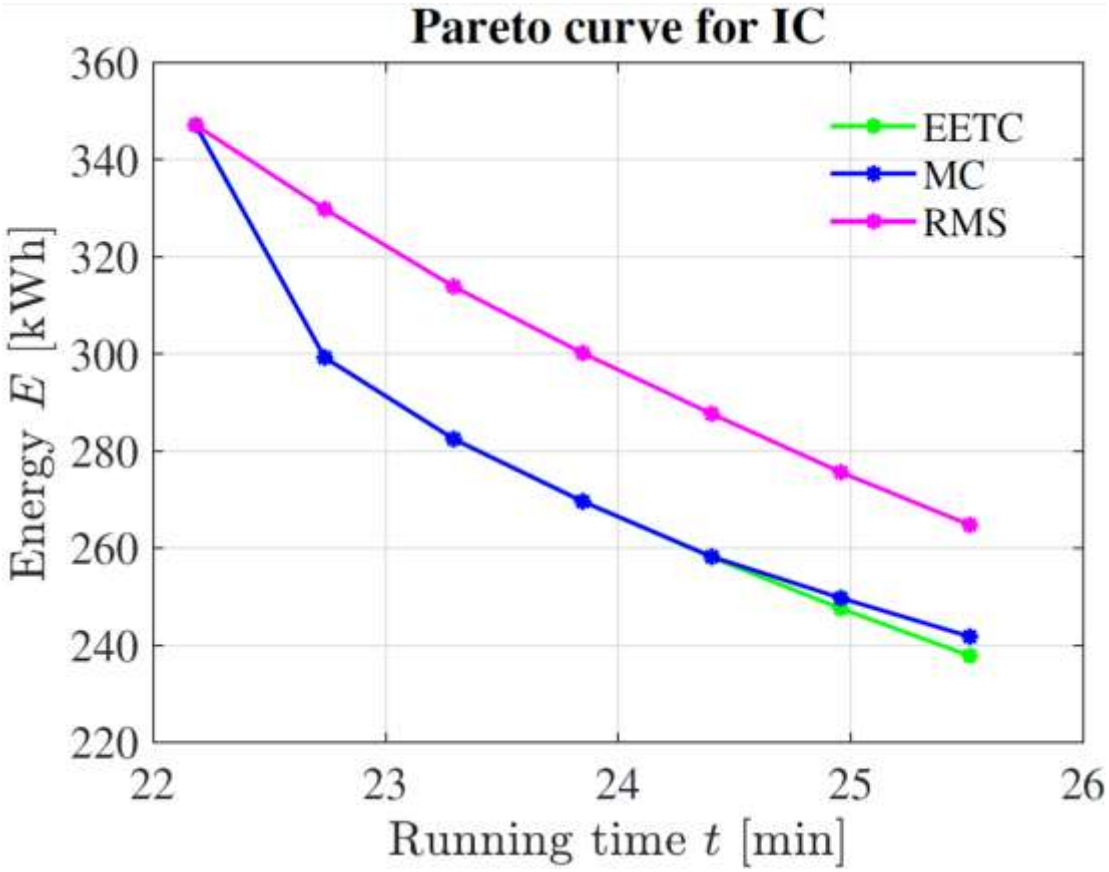


Figure 50: Scenario varying running time allowances (IC) Pareto curve

Like the scenario of the IC we varied the running time allowances for the SPR between 0% and 15% in step size of 2.5%. Table 33 and Figures 51 and 52 show the results of the SPR for this scenario. For all variations of the running time allowances, the EETC driving strategy is equal to the MC driving strategy. The Pareto curve also clearly shows the effect of the diminishing returns, because the highest energy savings are achieved when the running time is increased from the minimum running time to 2.5% allowance. Also note that the gradient of the curve for the RMS driving strategy is rather constant, while the MC/EETC curve really shows the effect of the diminishing returns with higher amounts of running time.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	399.8	0%	83.3	0%
EETC	409.8	2.5%	69.5	-16.6%
MC	409.8	2.5%	69.5	-16.6%
RMS	409.8	2.5%	78.2	-6.1%
EETC	419.8	5%	64.1	-23.1%
MC	419.8	5%	64.1	-23.1%

RMS	419.8	5%	73.3	-12.1%
EETC	429.8	7.5%	60.0	-27.9%
MC	429.8	7.5%	60.0	-27.9%
RMS	429.8	7.5%	69.2	-17.0%
EETC	439.8	10%	56.7	-31.9%
MC	439.8	10%	56.7	-31.9%
RMS	439.8	10%	65.4	-21.5%
EETC	449.8	12.5%	53.9	-35.3%
MC	449.8	12.5%	53.9	-35.3%
RMS	449.8	12.5%	62.1	-25.4%
EETC	459.8	15%	51.4	-38.3%
MC	459.8	15%	51.4	-38.3%
RMS	459.8	15%	59.0	-29.2%

Table 33: Results of the reference scenario (SPR) with varying running time allowances

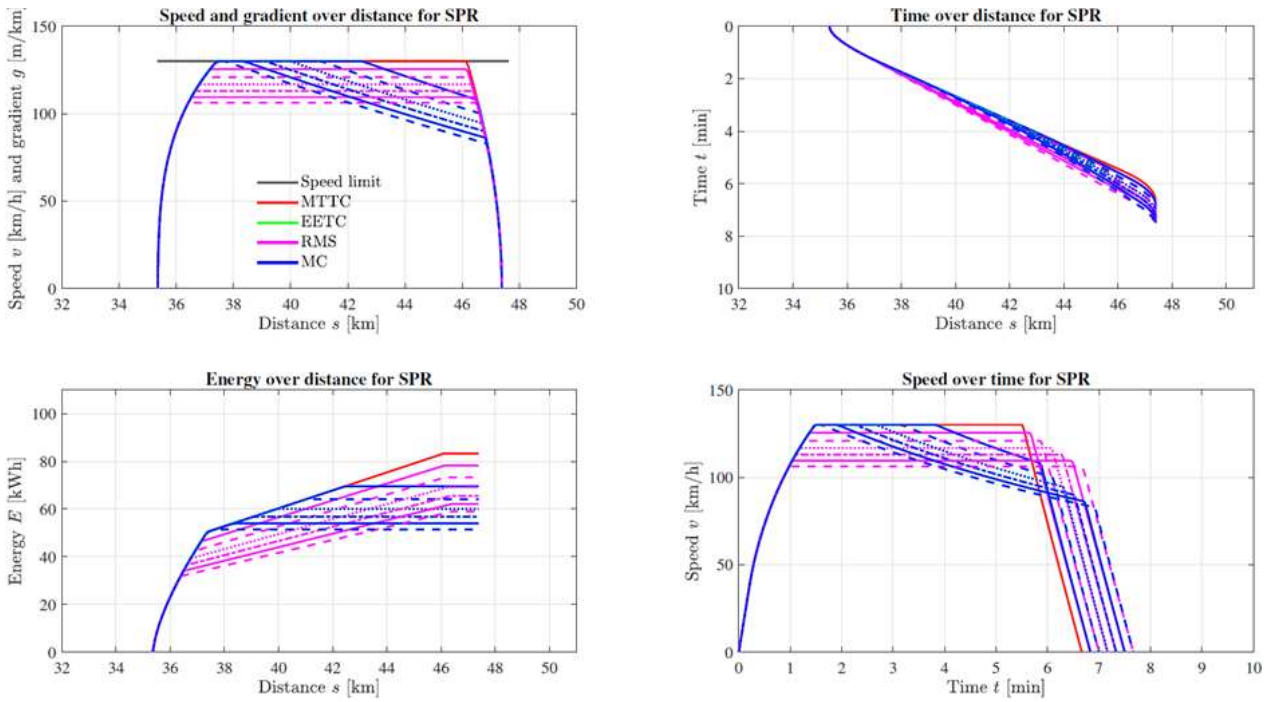


Figure 51: Scenario with varying running time allowances (SPR) with effects of the different driving strategies

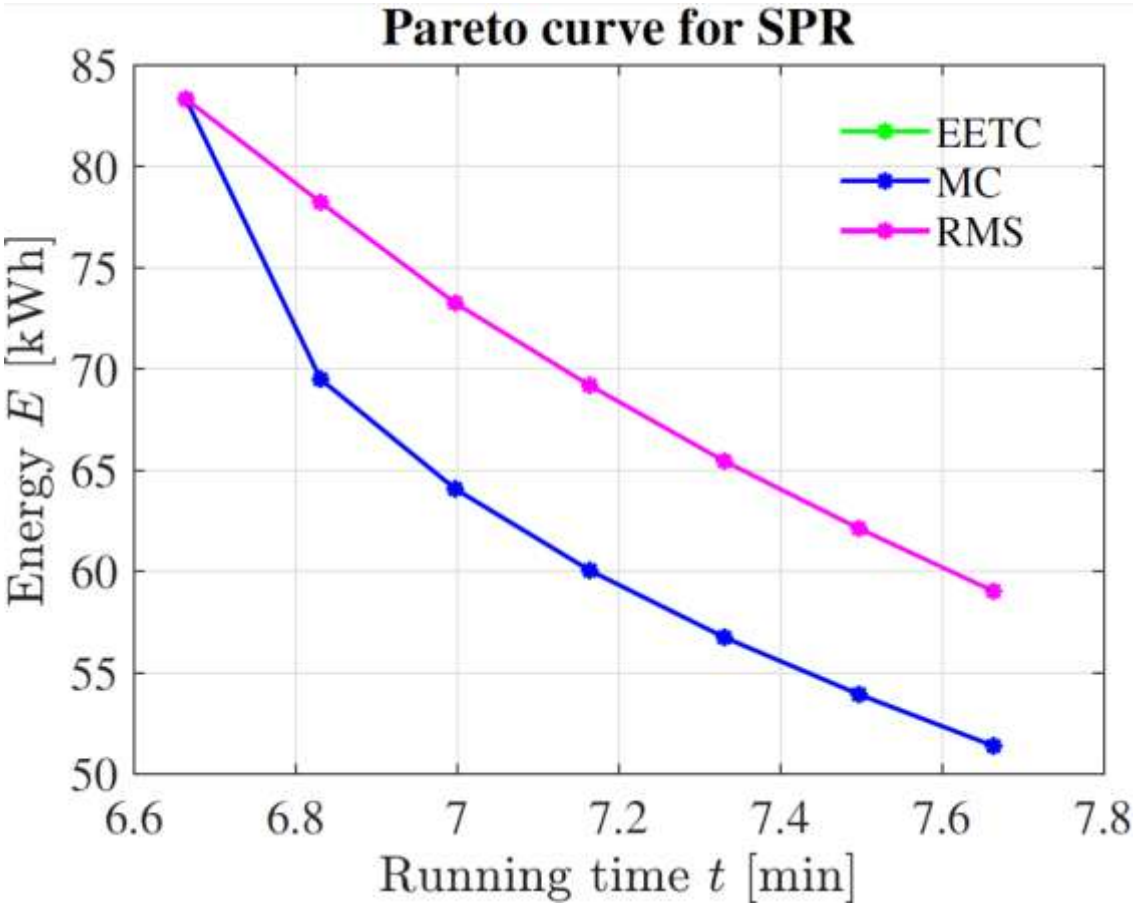


Figure 52: Scenario varying running time allowances (SPR) Pareto curve

Scenario: with varying performance on acceleration and braking for RMS and EETC

In this scenario the performance for acceleration and braking of trains is varied between 50% and 100% for the driving strategies RMS and EETC for the IC and SPR. A reduction in performance means that the train does not apply full traction or braking, but in accordance with the performance that is set. For instance, a performance of 90% means that the train applies maximum 90% of the traction force and power as well as the 90% of the available braking force. The running time allowance is set to 10% and no varying gradients and speed limits are considered here.

InterCity

Table 34 and Figure 53 show the result of this scenario for the IC where the performance is varied between 50% and 100%. In general, the results show that lower performance on acceleration and braking leads to a higher energy consumption, while given the same running time allowance (10%). Furthermore, the EETC driving strategy shows that less coasting is applied due to the reduced performance. For the RMS driving strategy the maximum cruising speed increased due to the reduced performance.

The reduction of the performance also influences the relative energy savings that can be achieved. For instance, for the EETC driving strategy with a performance of 100% compared to 90%, the

energy savings are 0.5% bigger. The difference between a performance of 60% compared to 50% is even 5.0% in energy consumption. For the RMS driving strategy the difference between 100% and 90% performance is also 5.0%, while the difference between the 60% and 50% is 3.1%. The difference in energy saving between EETC and RMS is about 10% for a performance of at least 70%. Therefore, the effect of the reduced performance is larger on the EETC than on the RMS driving strategy, especially for relatively low performances.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	1331.0	0%	347.1	0%
EETC 100% RP	1464.1	10%	258.1	-25.6%
RMS 100% RP	1464.1	10%	287.6	-17.1%
EETC 90% RP	1464.1	10%	259.5	-25.2%
RMS 90% RP	1464.1	10%	289.0	-16.8%
EETC 80% RP	1464.1	10%	261.4	-24.7%
RMS 80% RP	1464.1	10%	291.3	-16.1%
EETC 70% RP	1464.1	10%	263.8	-24.0%
RMS 70% RP	1464.1	10%	295.4	-14.9%
EETC 60% RP	1464.1	10%	269.5	-22.4%
RMS 60% RP	1464.1	10%	301.0	-13.3%
EETC 50% RP	1464.1	10%	283.7	-18.3%
RMS 50% RP	1464.1	10%	310.7	-10.5%

Table 34: Results of the scenario IC with varying performance for acceleration and braking for RMS and EETC (RP = reduced performance)

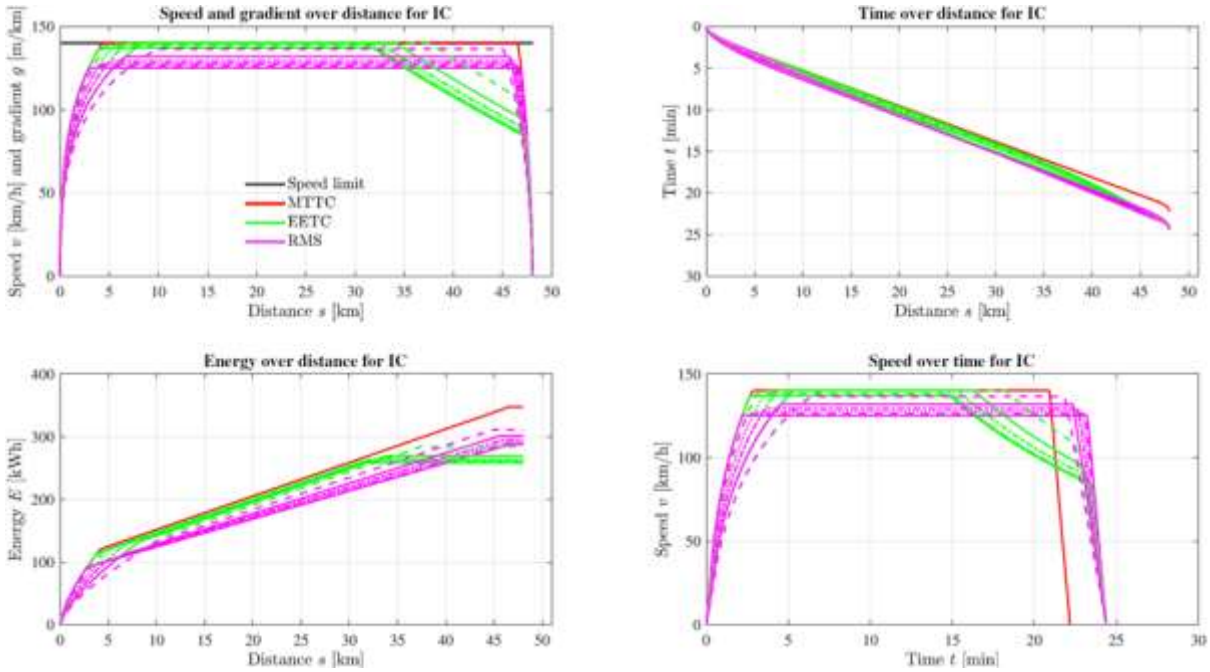


Figure 53: Scenario with varying performance for acceleration and braking IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Sprinter

Table 35 and Figure 54 show the results of the SPR for this scenario. The results for the EETC driving strategy show that the higher the performance, the higher the energy savings become. This is achieved by earlier coasting. Like the EETC driving strategy, the RMS driving strategy also leads to higher energy savings with higher performances. The energy savings are there achieved by a lower cruising speed.

The performance influences the relative energy savings. For instance, the difference between the 100% and 90% performance for both EETC and RMS is 2.4%. The energy savings for a performance of 60% compared to 50% are 16.1% for EETC and 5.4% for RMS. For a performance of at least 70% the EETC saves about 10% more energy compared to RMS. Like the results of the IC, the bigger the reduction in performance, the larger the effect on EETCS compared to RMS on relative energy savings.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	399.8	0%	83.3	0%
EETC 100% RP	439.8	10%	56.7	-31.9%
RMS 100% RP	439.8	10%	65.4	-21.5%
EETC 90% RP	439.8	10%	58.1	-30.2%
RMS 90% RP	439.8	10%	67.0	-19.6%

EETC 80% RP	439.8	10%	60.5	-27.4%
RMS 80% RP	439.8	10%	69.5	-16.6%
EETC 70% RP	439.8	10%	65.0	-21.9%
RMS 70% RP	439.8	10%	73.6	-11.7%
EETC 60% RP	439.8	10%	77.7	-6.7%
RMS 60% RP	439.8	10%	77.7	-6.7%

Table 35: Results of the scenario SPR with varying performance for acceleration and braking

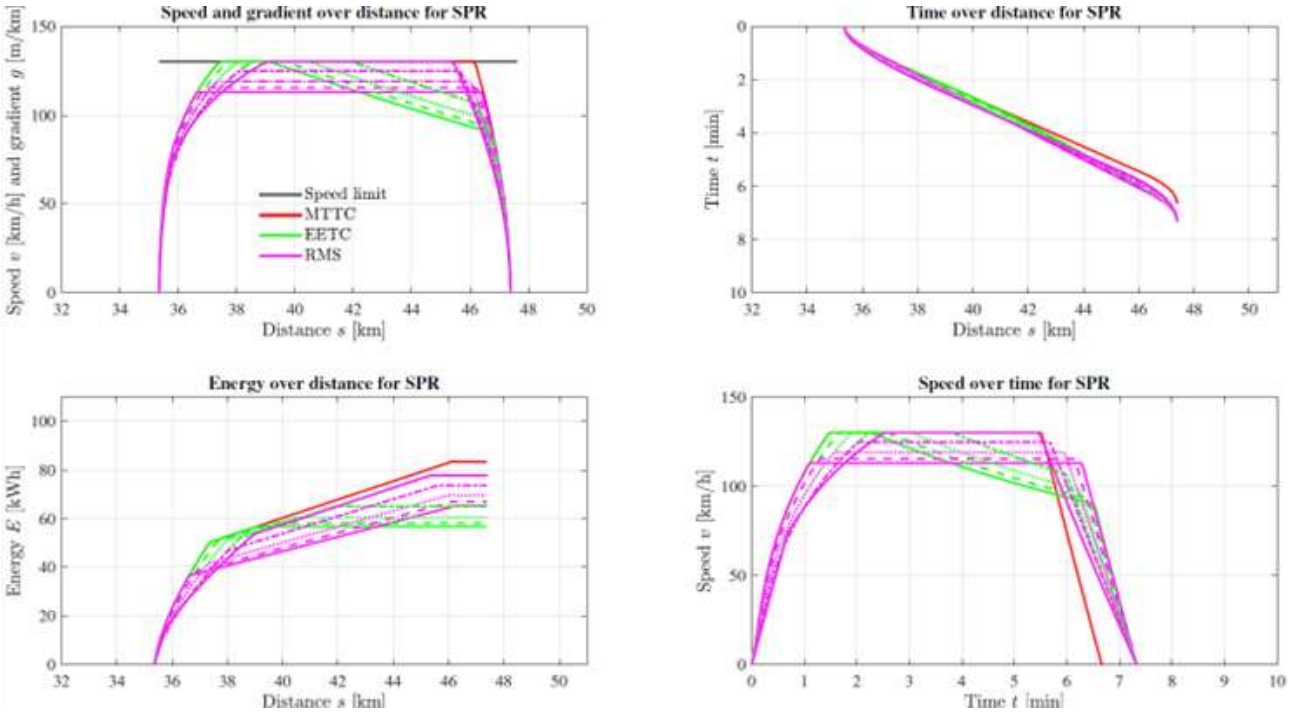


Figure 54: Scenario with varying performance for acceleration and braking SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Scenario: without varying gradients and with varying speed limits

In this scenario the varying speed limits are included for the IC and SPR for the different driving strategies (EETC, MC and RMS). The running time allowances are set to 10% and no varying gradients are considered.

InterCity

The results for the IC of this scenario are shown in Table 36 and Figure 55. The results indicate that EETC driving strategy leads to the lowest energy consumption. However, the MC driving strategy approaches the EETC driving strategy closely (0.08% higher in energy consumption). The EETC driving strategy has a cruising speed of 128.1 km/h, while the MC driving strategy applies a cruising speed of 130 km/h. The energy consumption of the RMS driving strategy is significantly bigger

compared to the EETC driving strategy (9.9%). Thus, the MC driving strategy is more energy-efficient compared to the RMS driving strategy in this scenario for the IC.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	1450.4	0%	353.5	0%
EETC	1595.5	10%	230.6	-34.7%
MC	1595.5	10%	230.8	-34.7%
RMS	1595.5	10%	253.4	-28.3%

Table 36: Results of the scenario without varying gradients and with varying speed limits IC without varying gradients and speed limits

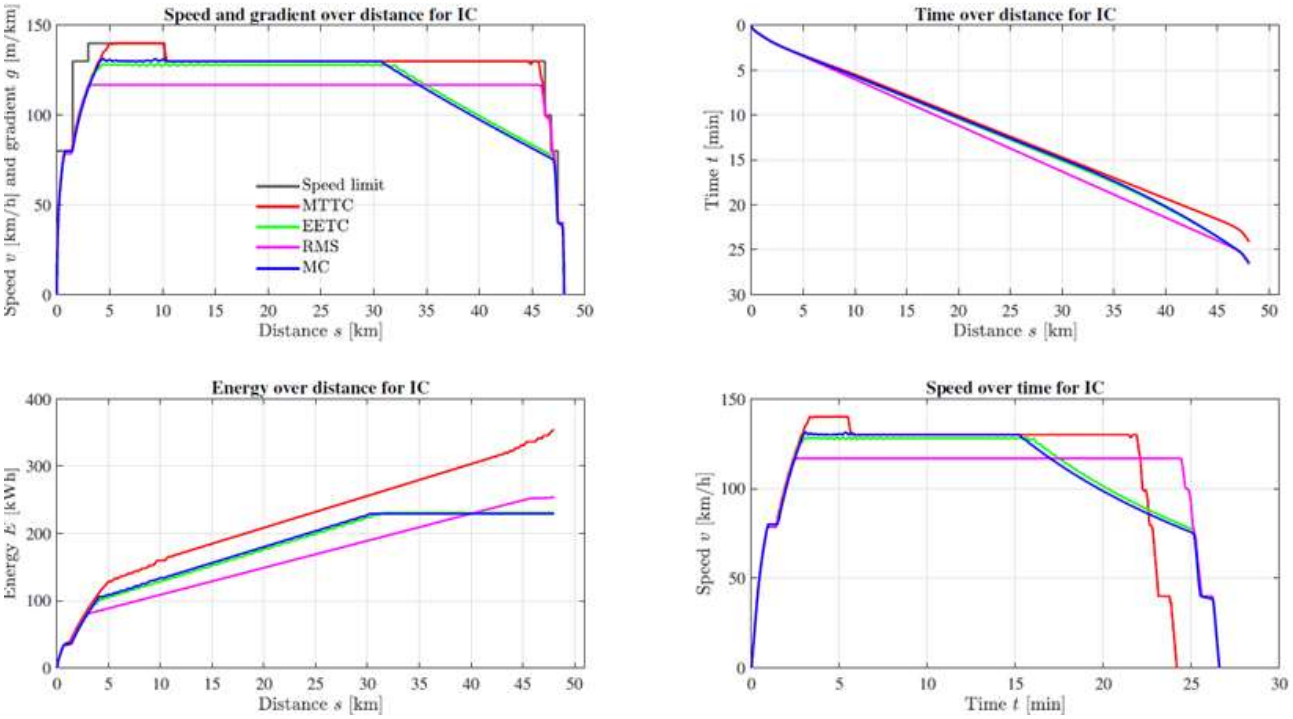


Figure 55: Scenario without varying gradients and with varying speed limits IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Sprinter

The results of this scenario for the SPR are shown in Table 37 and Figure 56. Like the reference scenario, the MC driving strategy is equal to the EETC driving strategy and leads to energy savings of more than 40% compared to the MTTC driving strategy. The RMS driving strategy leads to about 12.6% higher energy consumption compared to MC. Finally, the relative energy savings for the SPR (see Table 37) are bigger compared to the IC (see Table 36), because cruising is missing for the SPR.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	452.6	0%	83.3	0%
EETC	497.9	10%	52.3	-40.6%
MC	497.9	10%	52.3	-40.6%
RMS	497.9	10%	59.8	-32.0%

Table 37: Results of the reference scenario SPR without varying gradients and speed limits

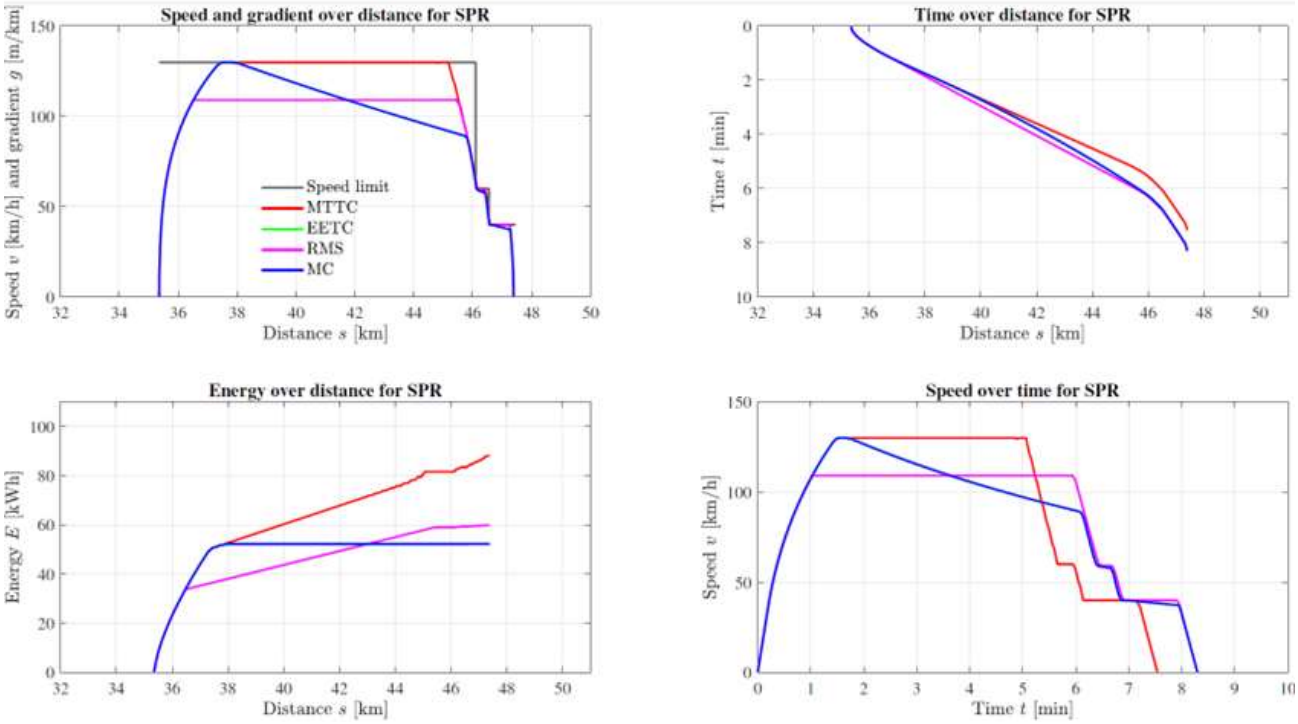


Figure 56: Scenario without varying gradients and with varying speed limits SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Scenario: with varying gradients and with varying speed limits

In this scenario both the gradients and speed limits are varied for the different driving strategies (EETC, RMS and MC) given 10% of running time allowances. The scenario is applied for the IC and SPR.

InterCity

Table 38 and Figure 57 show the result of this scenario for the IC. As can be seen in Figure x the train experiences fluctuations in the speed profile for the three eco-driving driving strategies due to the gradients and the accuracy of the algorithm with varying gradients (e.g., the number and location of the collocation points for the single-phase Radau pseudospectral method as described in Scheepmaker et al. (2020a)). The results also show that the EETC driving strategy leads to the biggest energy savings compared to the MTTC driving strategy (40.2%), although the energy savings of the MC driving strategy are relatively close to EETC (difference of 2.4%). Furthermore, the MC

driving strategy is more energy efficient compared to the RMS driving strategy. The extra energy savings are about 8.4%.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	1451.3	0%	392.9	0%
EETC	1596.4	10%	234.8	-40.2%
MC	1596.4	10%	240.5	-38.8%
RMS	1596.4	10%	262.5	-33.2%

Table 38: Results of the scenario with varying gradients and with varying speed limits IC without varying gradients and speed limits

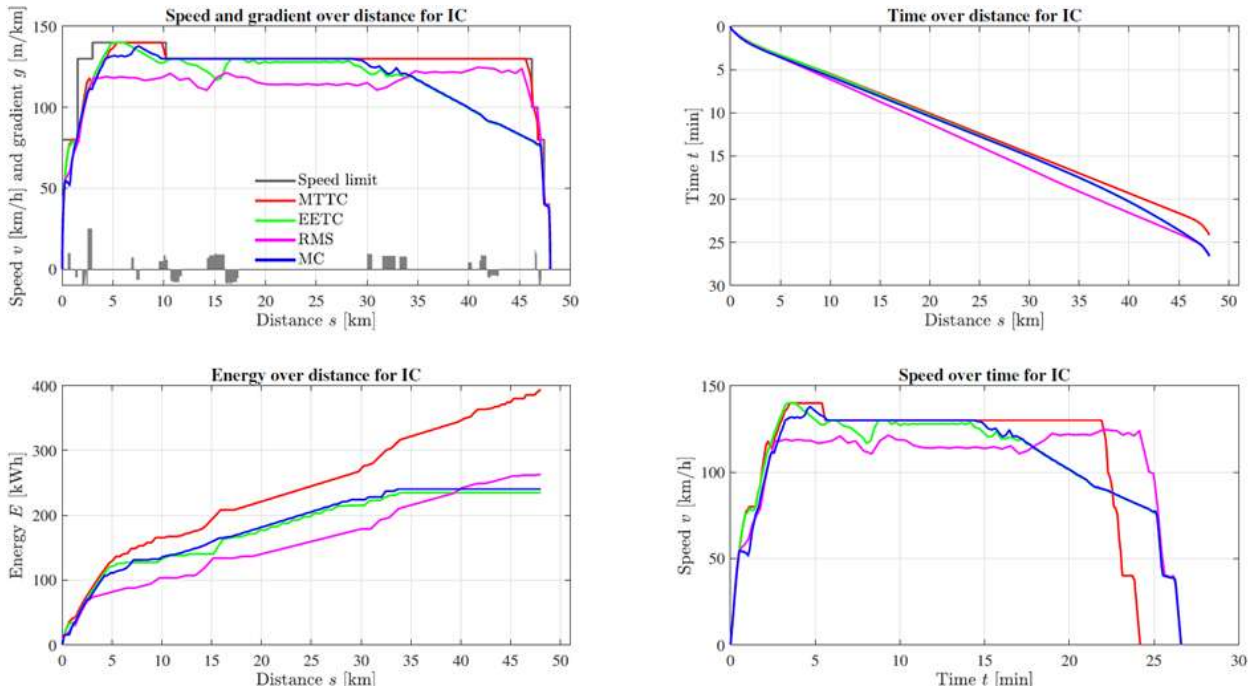


Figure 57: Scenario with varying gradients and with varying speed limits IC speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Sprinter

Table 39 and Figure 58 show the results of the SPR for this scenario. Like the IC, the speed profile of the SPR in Figure 58 clearly indicates the effects of the gradients in the fluctuations for the eco-driving strategies. There is a slight difference between the EETC and MC driving strategy for the SPR in this scenario. The EETC driving strategy has a short cruising phase at a speed of about 122 km/h, while the MC driving strategy accelerates to the speed limit of 130 km/h and has a short speed-holding at this speed. The difference in energy saving between the driving strategies EETC and MC is limited, EETC leads to about 0.7% higher energy savings compared to MC. The MC driving strategy saves about 14.1% more energy compared to the RMS driving strategy. Finally, the relative

energy savings of the eco-driving strategies of the SPR are slightly higher than the IC if we compare the results of Table 39 with Table 38, due to the shorter cruising phase.

Driving strategy	Running time [s]	Running time allowances	Traction energy consumption [kWh]	Energy savings compared to MTTC
MTTC	452.1	0%	89.0	0%
EETC	497.3	10%	52.3	-41.2%
MC	497.3	10%	52.7	-40.8%
RMS	497.3	10%	61.4	-31.0%

Table 39: Results of the reference scenario SPR with varying gradients and speed limits

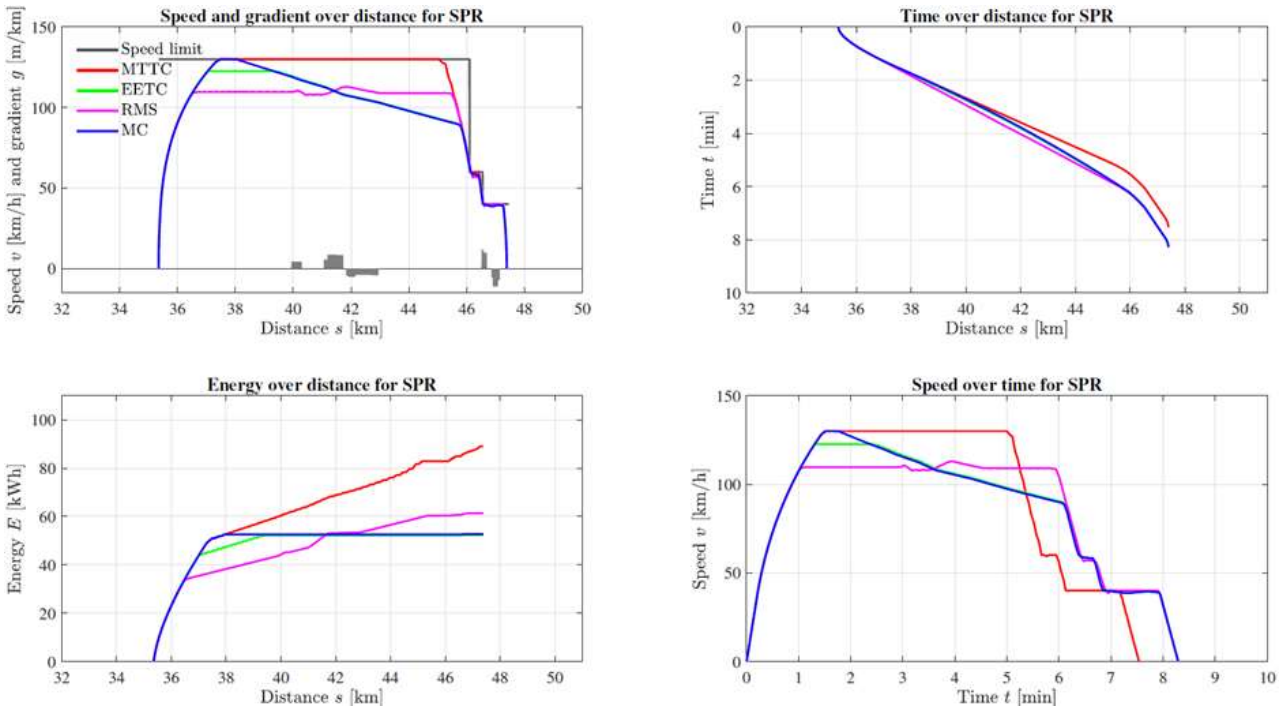


Figure 58: Scenario with varying gradients and with varying speed limits SPR speed-distance diagram (top left), time-distance diagram (top right), energy-distance diagram (bottom left), and speed-time diagram (bottom right)

Scenario: sensitivity analysis

In this scenario the reference driving strategy for a train driver with a C-DAS is changed from the MC to the RMS driving strategy. This means that not all train drivers with a C-DAS do apply for the MC driving strategy. Then we varied the percentage of train drivers that applies the MC instead of the RMS driving strategy to analyse the effect on the energy consumption. No varying gradients or speed limits are considered in this scenario, and the running time allowances are set to 10%.

InterCity

Table 40 and Figure 59 show the result of this scenario for the IC. The results indicate that the most energy can be saved if all train drivers apply the MC driving strategy (about 10% compared to 100%

RMS). In addition, the relationship is linear starting with 0% energy savings if 100% of the train drivers apply the RMS driving strategy up to 10% energy savings if 100% of the train drivers apply the MC driving strategy (increase of about 1% extra energy savings for every 10% increase in train drivers that apply the MC instead of RMS driving strategy).

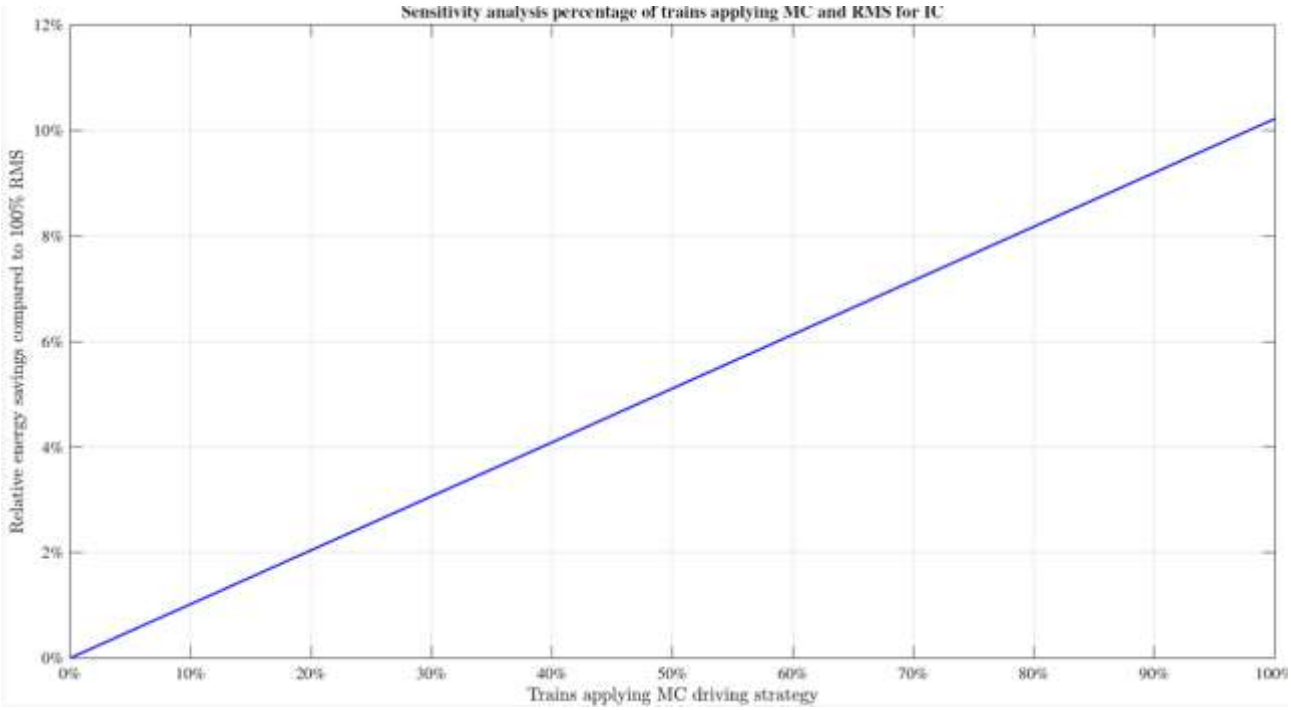


Figure 59: Sensitivity analysis of varying percentage of trains applying MC and RMS driving strategy and the relative energy savings compared to 100% RMS driving strategy for the IC

Scenario	Traction energy consumption [kWh]	Energy savings compared to 100% RMS
100% MC & 0% RMS	258.2	-10.2%
90% MC & 10% RMS	261.2	-9.2%
80% MC & 20 % RMS	264.1	-8.2%
70% MC & 30 % RMS	267.1	-7.2%
60% MC & 40 % RMS	270.0	-6.1%
50% MC & 50 % RMS	272.9	-5.1%
40% MC & 60 % RMS	275.9	-4.1%
30% MC & 70 % RMS	278.8	-3.1%
20% MC & 80 % RMS	281.8	-2.0%
10% MC & 90 % RMS	284.7	-1.0%
0% MC & 100 % RMS	262.5	0%

Table 40: Results of the sensitivity scenario for manual driving using C-DAS (varying the percentage of MC and RMS application by train drivers) for the IC

Sprinter

Table 41 and Figure 60 show the results of the SPR for this scenario. Like the IC scenario, the relative energy savings by extra train drivers applying the MC driving strategy linearly increases. E.g., 10% increase in the number of train drivers applying the MC driving strategy, leads to an extra energy saving of about 1.3%. At most 13.3% energy can be saved with 100% MC compared to 100% RMS.

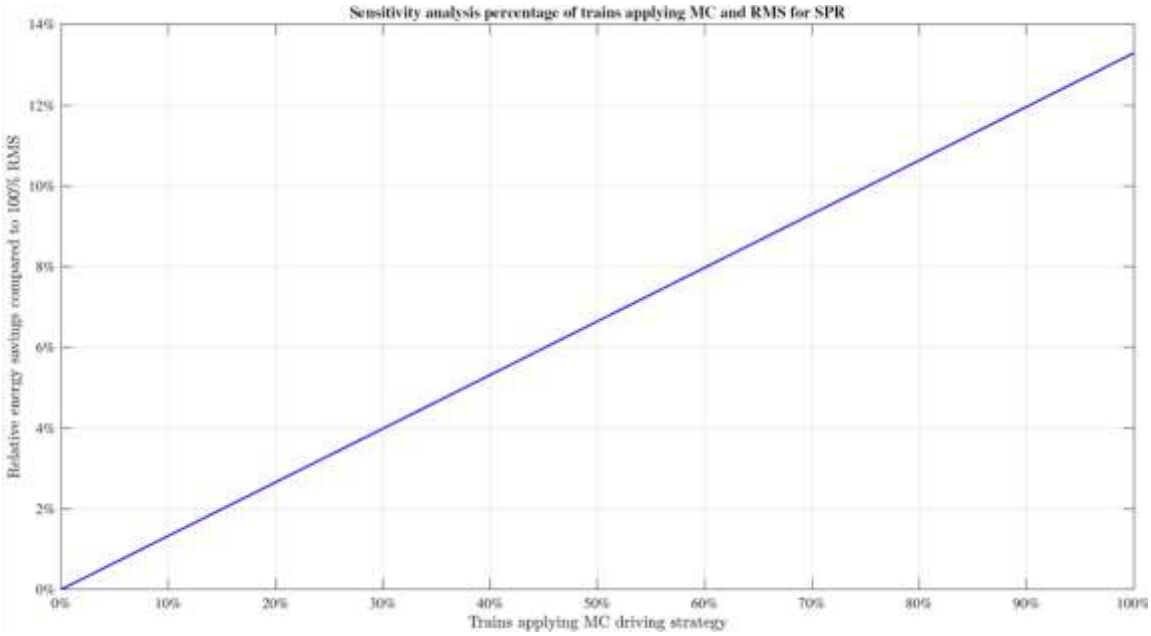


Figure 60: Sensitivity analysis of varying percentage of trains applying MC and RMS driving strategy and the relative energy savings compared to 100% RMS driving strategy for the SPR

Scenario	Traction energy consumption [kWh]	Energy savings compared to 100% RMS
100% MC & 0% RMS	56.7	-13.3%
90% MC & 10% RMS	57.6	-12.0%
80% MC & 20 % RMS	58.5	-10.6%
70% MC & 30 % RMS	59.4	-9.3%
60% MC & 40 % RMS	60.2	-8.0%
50% MC & 50 % RMS	61.1	-6.6%
40% MC & 60 % RMS	62.0	-5.3%
30% MC & 70 % RMS	62.8	-4.0%
20% MC & 80 % RMS	63.7	-2.7%
10% MC & 90 % RMS	64.6	-1.3%
0% MC & 100 % RMS	65.4	0%

Table 41: Results of the sensitivity scenario for manual driving using C-DAS (varying the percentage of MC and RMS application by train drivers)

This marks the end of the reporting of the results of this Appendix. We refer to chapter 6.3 for a summary of this report on energy efficiency, as well as a list of conclusions we draw from it.