Cost of railway capacity expansions in Norway as input to evaluation of Economic Feasibility of Automatic Train Operation

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Abstract

Growing demand for rail services is driving investments to improve sustainability, efficiency, and safety. Traditionally, these goals were pursued through large-scale infrastructure projects, but they are complex, costly, and prone to delays and budget overruns. Technologies such as Automatic Train Operation (ATO) are emerging as potential alternatives or complements, promising gains in punctuality, efficiency, and capacity. Limited research exists on the comparative economic feasibility of infrastructure and ATO. This paper develops a framework for comparing the costs and benefits of infrastructure investments and ATO, using key performance indicators (KPIs) that relate costs, both per kilometer and at project level, to capacity and punctuality improvements. The framework is applied to Norwegian cases, drawing on front-end analyses of infrastructure projects and ATO use cases. The results show that infrastructure remains more cost-effective for large-scale capacity increases, while ATO is more favorable for punctuality improvements and incremental efficiency, particularly in dense corridors. Findings suggest that infrastructure and ATO should be viewed as complementary: infrastructure providing the foundation for capacity expansion, and ATO enhancing reliability and efficiency. The study contributes a structured, KPI-based framework for comparative analysis and emphasizes the need for future research to incorporate broader benefits and reduce uncertainty around ATO costs.

Keywords : Automatic Train Operation; Railways; Investments; Costs

1. Introduction

The global demand for rail services is increasing, necessitating substantial investments in rail infrastructure projects to enhance sustainability, efficiency, reliability, and safety (Singh et al., 2021). However, these large-scale projects are frequently affected by cost overruns (Love et al., 2017) and involve a diverse range of professionals from multiple disciplines (Kwok, Anderson, and Ng, 2009), while also significantly impacting external stakeholders (Wu, Fang, and Li, 2015). Due to these complexities, rail infrastructure projects often span several decades and require budgets ranging from millions to billions of dollars (Locatelli, Invernizzi, and Brookes, 2017).

They are subject to significant uncertainties and risks, leading to frequent inaccuracies in time and cost forecasts (Bruzelius et al., 2002; Flyvbjerg, 2007; Locatelli, Invernizzi, and Brookes, 2017). The intricate nature of these projects stems from their extended life cycle, which progresses through multiple phases, including conception, design, construction, operation, maintenance, and eventual decommissioning (Pasetto and Giacomello, 2023). The involvement of numerous actors, such as designers, construction firms, operators, and maintenance providers, further amplifies the complexity (Pasetto and Giacomello, 2023).

New technologies are being explored as alternatives to large-scale rail infrastructure projects, aiming to deliver similar benefits in terms of operational efficiency, energy savings, passenger experience, and service capacity (Pollehn, Ruf, and König, 2021; Wang et al., 2022; Chaves, et al. 2024; Reichmann et al., 2025). One such technology is Automatic Train Operation (ATO) (Europe's Rail, 2024). While ATO holds the potential to optimize operations and enhance rail network performance (Singh et al., 2021; Morin, Olsson and Lau, 2024), its implementation also requires significant financial investments (Jernbanedirektoratet, 2023).

For instance, deploying driverless trains in Norway could be highly expensive due to the need to secure existing infrastructure. While costs could be reduced by focusing on high-density areas, there is limited research on the economic feasibility of ATO compared to traditional rail expansion. The purpose of this paper is the following:

1. Develop a framework to allow the comparison of the cost and benefits of traditional infrastructure rail investments and ATO.

2. Apply and test this framework to compare estimated rail traffic effects in the Norwegian setting using available information.
3. Propose improvements to this framework for further comparative analysis and future studies.

The subsequent section will cover the relevant literature and address the research gap. The methodology will follow. Results are then presented, continuing with discussion and conclusion.

2. Conceptual Overview

2.1 Benefits of railway projects

Railway projects can generate transformative economic and social benefits, particularly in regions with limited transport accessibility that restrict access to employment, healthcare, and education (Lucas et al., 2016; Cascetta et al., 2020). By enhancing connectivity between communities and urban centers, railways promote urban agglomeration and regional productivity (Kim and Sultana, 2015; Ciccone and Hall, 1996; Cascetta et al., 2020), facilitate supply chain efficiency by linking producers to wider markets (Hong et al., 2011; Cascetta et al., 2020), and attract foreign direct investment (Hong, 2007; Cascetta et al., 2020). They reduce transport costs, encourage industrial clustering, and support economies of scale (Baldwin and Forslid, 2000; Krugman, 1991; Cascetta et al., 2020).

Beyond these economic effects, minimizing travel time enhances passenger experience, encourages a shift from road to rail, and contributes to reduced congestion, lower emissions, and improved safety (Lyons, Jain, and Holley, 2007; Grimes and Young, 2013). Reliability and punctuality also play a critical role in attracting passengers (van Loon, Rietveld, and Brons, 2011). Surmařová et al. (2025) show that infrastructure upgrades on a specific corridor reduced travel time by 17%, increased service frequency by 50%, and raised rail's modal share from 14–23% to 19–32%. However, the success of rail projects is deeply influenced by their urban and geographical context, with factors such as population density, topography, existing infrastructure, and regulatory frameworks significantly shaping costs, feasibility, and outcomes (Surmařová et al., 2025).

2.2 Measuring the Success of Railway Projects and the Role of KPIs

Understanding regional characteristics is essential for interpreting project impacts, particularly in the Norwegian context where performance measurements are increasingly used to evaluate both economic efficiency and broader societal value. There is a shift toward broader and more nuanced performance metrics, which include customer-centered evaluations and assessments of railways' contributions to societal goals (Fagerhaug and Olsson, 2005). For example, Volden (2018) shows that some Norwegian rail projects had suboptimal outcomes in terms of ridership and capital cost but were still deemed viable due to their alignment with government sustainability and efficiency objectives. This highlights the importance of considering broader criteria beyond traditional economic returns.

At the same time, modernizing passenger rail systems through infrastructure upgrades or novel rolling stock investments entails significant fixed costs (Grimes and Young, 2013). Constructing new High-Speed Railway lines can cost up to 23 million euros per kilometer, while upgrading conventional lines to High-Speed standards may reach 17.2 million euros per kilometer (Vrána et al., 2024; Surmařová et al., 2025). Such costs are often underestimated during project appraisal, while projected demand and benefits tend to be overestimated (Vickerman, 2018). Flyvbjerg (2007) found that rail projects have the highest average cost overruns (44.7% above estimates) and the lowest accuracy in demand forecasts, with traffic averaging 39.5% below projections and ridership falling 50.8% short of forecasts. These discrepancies expose projects to significant financial risks, as fare revenues rarely offset escalating costs, intensifying financial uncertainty (Flyvbjerg, 2007).

To address these challenges, evaluation frameworks must go beyond final construction cost and incorporate more comprehensive, life-cycle perspectives (Love et al., 2017). Efficiency in rail infrastructure requires both adaptive project delivery strategies and broader policy frameworks. Cost-benefit analysis, while central, cannot capture the full range of project outcomes, particularly those related to strategic or societal goals (House, 2000; Heinzerling and Ackerman, 2002; Volden, 2018). Evidence from Norway shows that cost-benefit efficiency has limited influence on project prioritization, with decision-makers weighing additional considerations such as sustainability and relevance (Nyborg, 1998; Eliasson et al., 2015; Volden, 2018).

This is where key performance indicators (KPIs) play a critical role. Measuring performance through KPIs is an established practice across sectors (Andersen, 1999; Bitici et al., 2012), structured around three components: (1) defining clear criteria, (2) benchmarking outcomes, and (3) implementing corrective measures where necessary (Choong, 2014). Over time, these indicators have evolved from traditional financial measures to include knowledge-based, non-financial dimensions, shifting the emphasis from lagging to leading indicators (Bitici et al., 2012).

In the railway industry, KPIs are used by infrastructure managers, planners, and operators across operational and strategic domains such as maintenance, timetable performance, customer satisfaction, and sustainability (Stenström, Parida and Galar, 2012; Goverde, Corman and, D'Ariano, 2013; Shan, Besinovic, and Schönberger, 2024). Timetable performance and punctuality are critical, with infrastructure occupation and capacity utilization serving as fundamental measures (UIC-406, 2004; Goverde, Corman and, D'Ariano, 2013; Solinen, Nicholson and Peterson, 2017). High utilization indicates efficiency but also reduces resilience to disruptions.

Railway infrastructure KPIs can broadly be classified into managerial indicators, covering reliability, availability, maintainability, financial, organizational, and safety aspects, and condition indicators, covering physical infrastructure categories such as substructure, superstructure, rail yards, electrification, signaling, and ICT systems (Stenström, Parida and Galar, 2012). Benchmarking is also widely applied, particularly for safety performance, enabling comparisons across railroads to identify risks and best practices. Lin et al. (2023) emphasize that systematic and publicly available safety data, including traffic levels, accident records, and accident consequences, is essential for meaningful benchmarking.

In sum, overly rigid or narrow performance metrics can distort outcomes: excessive focus on cost reduction may compromise quality and long-term functionality, while prioritizing benefits may lead to overbuilt or unaffordable projects (Klakegg and Olsson, 2010). The evaluation of rail projects must therefore integrate a holistic set of KPIs, encompassing both financial and non-financial criteria, to capture the multi-dimensional nature of success and ensure relevance for diverse stakeholders.

2.3 On ATO and large governmental investments in Norway

ATO comes in different forms. IEC 62290-1 defines four levels of automation, referred to as GoA levels (Grades of Automation):

- GoA1: The train driver operates the train manually, possibly with the assistance of driving advisory systems.

- GoA2: Acceleration, deceleration, and stopping are automated. The train driver remains responsible and intervenes if necessary.
- GoA3: The ATO system operates the train independently, but a driver is present and handles emergency situations.
- GoA4: The ATO system operates the train independently and no staff needs to be present on the train.

The Norwegian Railway Directorate has assessed the feasibility of implementing ATO across the national network, focusing on the higher levels of automation, GoA3 and GoA4.

Such large-scale government investments in railway infrastructure, rolling stock, and digital systems are subject to a rigorous appraisal process to ensure "quality at entry" before moving forward. In Norway, this begins with the preparation of a Conceptual Appraisal (KVU), which outlines the problem definition, needs assessment, overall strategy, and an evaluation of possible alternatives. The KVU also includes a socio-economic analysis that considers three main dimensions: societal effects (travel time savings, changes in emissions, accident rates), direct governmental costs (investment, operations, and maintenance), and business impacts on stakeholders such as train operators.

To further ensure robust decision-making, the Norwegian State Project Model mandates external quality assurance for all public investment projects exceeding 90 million Euros. This includes two formal checkpoints: QA1 and QA2 (Samset and Volden, 2016). QA1 evaluates the choice of concept prior to the government's decision to proceed, ensuring political oversight and validating the quality of documentation. If the project passes QA1, it advances into the pre-project phase, where a more detailed project plan is developed.

QA2 is conducted at the end of the pre-project phase, before submission to Parliament for funding approval. It focuses on the realism of cost estimates and project governance. At this stage, the ministry or responsible agency submits management plans, alternative contract strategies, benefit-cost analyses, and refined cost estimates. External consultants assess key success factors, identify risk areas, quantify cost uncertainties, and provide recommendations on the project's cost frame, risk management, and contingency reserves (Welde and Engebø, 2024).

Within this framework, evaluating railway projects, especially ATO implementations, requires comprehensive performance measurement tools. Economic indicators such as cost per train-km, punctuality, capacity utilization, regularity, and revenue generation are commonly used to assess cost-effectiveness (Fagerhaug and Olsson, 2005). However, integrating broader indicators that capture societal impact, such as sustainability and public value, is essential for capturing the full picture. Combining both types of indicators enables more nuanced causal analysis, reducing the risk of overemphasizing isolated metrics (Fagerhaug and Olsson, 2005). This multidimensional approach is particularly relevant for comparing traditional rail investments with ATO-based projects, and the following section will outline the research gap in this area.

2.4 Research Gap

Studying the cost of railway capacity expansion requires defining metrics for both cost and capacity. Cost per length unit, such as per meter of new track, is well established, varying by speed requirements, urban density, and infrastructure complexity. While capacity increases justify many expansions, the cost per additional train is rarely quantified. High-speed railway construction can range from 10 to 45 million EUR per kilometer, with some cases reaching 70 million EUR (transport.ec.europa.eu).

Railway capacity is influenced by infrastructure, timetabling, and punctuality policies. The UIC (2004) states that "capacity as such does not exist" but depends on utilization. Researchers use metrics like headway (train spacing) and capacity utilization (track occupancy) (Knutsen et al., 2024). The UIC Code 406 applies a timetable compression method to measure utilization. Capacity expansion can accommodate more trains, improve punctuality, or enhance flexibility. This can be achieved through new infrastructure or better use of existing resources (Lai and Barkan, 2011; Lindfeldt, 2015). Comparing these approaches requires detailed data. This study adopts a customer-focused metric: (cost per km) / additional trains before and after expansion.

Optimizing existing infrastructure includes improved timetabling, simulations, and variance reduction. While ATO is gaining interest for efficiency, its economic evaluation versus traditional expansion remains limited (Singh et al., 2021; Europe's Rail, 2024). Cost estimates for ATO in Norway suggest significant investment (Jernbanedirektoratet, 2023), but its cost-effectiveness compared to track expansion is unclear. Rail projects often face cost overruns and demand overestimations (Flyvbjerg, 2007; Vickerman, 2018) but yield societal benefits (Surmařová et al., 2025).

A key research gap exists in evaluating railway investments beyond infrastructure expansion by incorporating technological advancements like ATO. This study takes a train customer perspective, using the number of trains as a visible capacity metric. The applied metric is (cost per km) / number of additional trains, where cost relates to infrastructure expansions, and train increase is measured before and after construction. Additionally, initiatives to optimize existing infrastructure, such as improved timetabling, timetable simulations, and operational precision, highlight alternatives to traditional expansion.

Thus, this study compares ATO and conventional investments, analyzing the cost per additional train to evaluate financial feasibility and strategic viability. By addressing this gap, it provides insights for policymakers to optimize railway investments.

3. Methodology

3.1 Research design

The data used in this study comes from different analyses and evaluations of large governmental investments in Norway, all publicly available. Evaluations of government investments are done in relation to the Concept research program. Data on expected benefits of ATO is derived from a Conceptual Appraisal study (KVU) done as preparation of a possible future Norwegian investment in ATO. Both datasets are related to the Norwegian quality assurance scheme for large governmental investments. One KVU for ATO is studied in some detail. Cost and benefits from railway infrastructure investments are based on five different evaluations describing six different infrastructure projects. These evaluations compare cost and benefits defined in QA2 from the front end of the projects and achieved outcomes roughly two years after project implementation.

The intention of the paper is to compare costs for capacity improvements. Naturally, such comparison involves several assumptions and simplifications. To begin with, the cost for ATO is only based on estimates, while the cost for infrastructure projects is available both as estimated and actual. All prices are indexed to 2023-kr with a road and rail infrastructure specific index (Bulygina, 2025). For capacity estimates of infrastructure investments, both the expected and actual number of trains and punctuality are available for infrastructure projects. For ATO, the capacity information that is available is estimated change in punctuality and headway, based on simulations. Ideally, the estimated capacity for infrastructure projects would also be quantified based on similar types of simulations. This proved to be difficult, as such studies may not be publicly available, and even when studies were obtained, the tools and methods for capacity analysis simulations have changed over the years.

As shown in table 1, a direct comparison is challenging due to differences in data sources and evaluation methods. The paper does not aim to present a perfect equivalence, but rather to explore how different key performance indicators (KPIs) can be used to support meaningful comparisons. For instance, we test alternative KPIs such as:

- Estimated cost per km vs. capacity increase,
- Total cost vs. number of additional trains,
- Punctuality improvement per unit cost

Table 1 - Comparative metrics for infrastructure and ATO

Topic	Expected or actual	Infrastructure	ATO
Costs	Expected	Expected, based on mature analyses	Expected, based on rough estimates
	Actual	Final	
Line/system length		5-23 km	200-4500 km
Traffic quality	Expected	Punctuality	Delays
	Actual	Punctuality	
Capacity	Expected	Number of trains	Headway
	Actual	Number of trains	

These indicators are proposed as tools to bridge gaps between dissimilar evaluation approaches and data structures. While some approximations are unavoidable, we believe the analysis is valuable for three reasons. First, it contributes to the relatively limited research on the benefits of infrastructure investments, particularly metrics such as cost per additional train. Second, it provides one of the first publicly accessible insights into ATO costs and benefits for conventional rail, a domain where most data remain scarce or unpublished. Finally, it introduces and tests KPIs like “capacity cost efficiency” and “punctuality cost efficiency” to better enable comparisons between projects evaluated using different methodology.

We are also not aware of studies that showed the cost of adding an additional train. As for ATO cost, this is a rather new area with few examples from conventional rail, even though it is well established for metros. Work on establishing a business case for ATO on conventional rail (EuRail, 2025) has so far not identified publicly available data on either cost or benefits. There are publications on general expectations (Morin, Olsson and Lau, 2024) but few specific numbers. The study thus proposes potential indicators to compare studies that use different metrics for cost and benefit. As shown in table 2, we investigate the use of "capacity cost efficiency" and "punctuality cost efficiency" as key performance indicators for this type of comparison.

Table 2 - Indicators for infrastructure and ATO

Topic	Common Indicator	Specific indicator infrastructure	Specific indicator ATO
Cost	Cost/km	Estimated cost/km Actual cost/km	Estimated cost/km
Capacity	Capacity utilization, headway	Increase in frequency	Change in headway
Punctuality	Delay (minutes/hours) Punctuality (%)	Punctuality change	Punctuality change
Capacity cost efficiency	Not established	(Estimated cost/km)/additional trains (Actual cost/km)/additional trains	(estimated cost/km)/capacity increase
Punctuality cost efficiency	Not established	(Actual cost/km)/punctuality change	(Estimated cost/km)/punctuality change

3.2 Validity and reliability of the research design

The methodological choices in this study have clear implications for validity and reliability. The core challenge is that the two types of projects under comparison, railway infrastructure upgrades and ATO implementation, are evaluated using different approaches, levels of maturity, and data availability. While infrastructure projects are assessed through the Norwegian quality assurance scheme with both estimated and realized data, ATO is still at a conceptual appraisal stage, where only estimated costs and simulated performance outcomes are available.

From the perspective of internal validity, this asymmetry means that the comparison cannot be regarded as fully equivalent. For infrastructure projects, the benefits are drawn from observed traffic volumes and punctuality after implementation, while for ATO they are based on modeled headway reductions and punctuality gains. Simulation studies provide useful projections but rely on assumptions that may not be held in practice. The maturity of cost estimates also differs: infrastructure costs are based on both detailed pre-decision assessments and ex-post figures, while ATO costs rely on preliminary estimates. These methodological differences limit the precision of the comparison but are addressed by focusing on relative efficiency measures, such as cost per additional train or punctuality improvement per unit cost, rather than absolute values.

External validity, or the generalizability of findings, is also constrained. The data are drawn from the Norwegian context, where evaluation practices follow a highly formalized QA framework. Results may therefore not fully translate to other countries with different institutional settings, costing practices, or traffic conditions. Yet, the introduction of derived indicators such as "capacity cost efficiency" and "punctuality cost efficiency" enhances transferability by offering a standardized lens through which different types of projects may be assessed across contexts.

In terms of reliability, the use of publicly available government evaluations increases transparency and reproducibility. Infrastructure project data can be cross-checked against official QA2 documents and evaluation reports, ensuring consistency in reporting methods. For ATO, however, reliability is weaker due to the scarcity of empirical data and reliance on simulations. Different simulation tools and assumptions could produce different results, making replication challenging. To address this, the study clearly documents the sources and assumptions underpinning the ATO estimates and indexes all financial figures to 2023-kr to ensure comparability.

Taken together, the methodological choices mean that the study should be understood as exploratory rather than conclusive. While the results do not provide a perfect equivalence between infrastructure investments and ATO, they highlight the potential of alternative KPIs to create meaningful comparisons despite data asymmetries. By openly acknowledging the limitations in validity and reliability, the study strengthens its credibility and contributes a transparent basis for further research, particularly as more empirical data on ATO implementation in conventional rail becomes available

4. Results

4.1 Cost and benefits of infrastructure developments in Norway

Table 3 shows key metrics for recent Norwegian railway infrastructure investments. The purpose is to get indications of punctuality and capacity improvements in relation to investment costs, both estimated and actual. The input values are based on evaluations of the projects done through the Concept research program at NTNU (Concept, 2025).

Table 3 - Key metrics of recent Norwegian railway infrastructure investments (cost converted to 2023 NOK). Frequency values in bold are for trains per day, while non-bold values are trains per hour.

	Barkåker-Tønsberg	Farriseidet-Porsgrunn	Lysaker Sandvika	Sandnes-Stavanger	Sandvika-Asker	Gevingåsen
Period	2009-2011	2012-2018	2007-2011	2006-2009	2001-2005	2009-2011
Type of investment	Single to Double	Single to Double	Double to Quadrouble	Single to Double	Double to Quadrouble	New single (tunnel)
Percent tunnel	0	66	82	0	77	77
Expected cost (2023 MNOK)	2465	9545	5028	2613	8904	1089
Actual cost (2023 MNOK)	2475	9509	4768	3509	6372	1118
km railway	5.8	22.3	6.7	14.5	9.5	5.70
Estimated cost/km (MNOK)	425	428	751	180	937	191
Actual cost/km (MNOK)	427	426	712	242	671	196
Punctuality before	Not quantified	97	92	93	84	90
Expected punctuality after	95	95	92	98	95	93
Actual punctuality after	Not quantified	99	93.5	94.5	89	90
Frequency before	**21**	**48**	11	2	20	5.4
Expected frequency after	Not quantified	**120**	19	4	28	8
Expected frequency incr. %	Not quantified	150.0 %	72.7 %	100.0 %	40.0 %	48.1 %
Actual frequency after	**22**	**50**	13	4	24	5.4
Actual frequency increase %	4.76 %	4.17 %	18.18 %	100.00 %	20.00 %	0.00 %
Estimated (cost/km)/additional train	Not quantified	**6**	94	90	117	74
Actual (cost/km)/additional train	**427**	**213**	356	121	168	No change
Estimated (cost/km)/capacity increase	Not quantified	285	1 032	180	2 343	397
Actual (cost/km)/capacity increase	8 960	10 234	3 914	242	3 353	No change
Estimated (cost/km)/punctuality	Not quantified	No increase	No change	36	85	64
Actual (cost/km)/punctuality	Not quantified	4 755	3 179	2 339	1 274	No change
Estimated cost/additional train	Not quantified	**133**	629	1 307	1 113	419
Actual cost/additional train	**2 475**	**4 755**	2 384	1 754	1 593	No change
Estimated cost/capacity increase in %	Not quantified	64	69	26	223	23
Actual cost/capacity increase %	520	2 282	262	35	319	No change
Estimated cost/punctuality increase	Not quantified	No increase	No change	523	809	363
Actual cost/punctuality increase	Not quantified	4 755	3 179	2 339	1 274	No change

4.2 Costs and benefits of deploying ATO in Norway

A Conceptual Appraisal study on ATO has been carried out as a part of the Norwegian quality assurance scheme for large governmental investments (Jernbanedirektoratet, 2023). The purpose of the study was to provide the ministry of transport with a basis for deciding if any ATO concepts were suitable in Norway. The concept selection study includes a socio-economic analysis of variants of future ATO implementation.

The estimated total investment for full-scale deployment is NOK 34.3 billion, of which NOK 24 billion would be allocated to trackside infrastructure upgrades (Jernbanedirektoratet, 2023). With approximately 4,200 kilometers of railway, this equates to an average of NOK 5.7 million per kilometer to enable ATO functionality. In addition to the full automation options, more incremental approaches such as GoA1 and GoA2 are under consideration. GoA1, which supports drivers with real-time decision guidance, is estimated to cost NOK 1,104 million, while GoA2, involving driver-supervised automated operation, would require an investment of NOK 2,290 million (Jernbanedirektoratet, 2023)

4.2.1. Alternatives and related costs of ATO implementations

The study analyzed three main concepts, and some sub-concepts. The three main alternatives were:

A: Connected Driver Advisory System (C-DAS): The alternative contains solutions for driver support that are digital and in real time but does not imply that the train is self-driving. This corresponds to a kind of GoA1.

B: Self-driving train: The concept implies that the train runs automatically between stops, but there is a driver present who initiates and monitors the automatic driving. The responsibility for the safety of the train remains with the driver. This corresponds to GoA2.

C: Driverless trains completely or partially without on-board personnel. The train is self-driving, and the technical system has taken over responsibility for the train's movements. This corresponds to GoA3 or 4, and the study does not make a difference between the two.

In alternative A, the driver receives continuous, real-time guidance from a connected driver assistance system. The driver guidance system not only provides real-time data but also offers decision support by integrating traffic and infrastructure information from the Traffic Management System (TMS) with data from the train itself. It then calculates the optimal driving strategy and displays the recommendations in the cab. This allows the driver to adjust speed and optimize driving in real time.

The estimated cost for implementing driver support in alternative A is structured around several components. As shown in table 4, the signal technical infrastructure is projected to cost 487 MNOK, while implementation costs, including the base estimate and expected additions, amount to 387 MNOK. The median expected cost (P50 estimate) is 1,049 MNOK, with an additional uncertainty provision of 43 MNOK, bringing the total to 1,092 MNOK. To account for potential cost variations, a more conservative estimate (P85, indicating that it is 85% probability that the investment can be made for this cost or less) includes an additional provision of 251 MNOK, leading to a possible upper cost of 1,344 MNOK. The final expected cost, approximately aligned with the P50 estimate, is 1,104 MNOK. The small difference between P50 and expected cost comes from asymmetries in the cost estimate, where higher cost is more likely than lower. Alternative A with C-DAS is a far less complex installation in a train than an ATO installation which is included in alternatives B and C.

Table 4 - Cost comparison of the main alternatives

	Alternative		
Cost item (million NOK excl. VAT)	A	B	C
Technical infrastructure signalling	487	487	487
Onboard C-DAC or ATO	175	1 067	1 067
Implementation cost	387	500	680
Infrastructure along the line			23 842
Infrastructure at stations			2 749
Safety equipment onboard			900
Base estimate	1 049	2 054	29 726
Expected additional cost	43	212	4 137
P50 estimate	1 092	2 266	33 863
Contingency	251	524	11 090
P85 estimate	1 344	2 790	44 953
Expected cost	1 104	2 290	34 296

In alternative B, self-driving trains operate under driver supervision. The train operates largely autonomously, with a computer controlling its movement while the driver oversees operations. The driver is responsible for initiating automatic driving, managing door operations, and taking manual control when necessary. This option introduces automated train operation along a predefined route, with real-time adjustments based on factors such as speed and other operational parameters to optimize performance. The system automatically regulates train movement, enabling it to operate more efficiently. For alternative B, the cost of signal technical infrastructure for ATO is projected at 487 MNOK as in alternative A, while onboard equipment amounts to 1,067 MNOK. The final expected cost, approximately aligned with the P50 estimate, is 2,290 MNOK.

In alternative C, the train operates automatically, handling all functions, including starting and stopping. At Grade of Automation 3 (GoA3), onboard staff are responsible for opening and closing doors and can assume manual control in case of deviations or system errors. In restricted areas, such as depots and turning facilities, the trains can operate without onboard personnel. At Grade of Automation 4 (GoA4), the trains can run entirely unmanned, with safety ensured through various technical solutions.

For alternative C, the cost of signal technical infrastructure for ATO and onboard equipment are the same as for alternative B. Among other costs, ATO requires connection to both the acceleration system as well as the braking system (interface to ETCS). This also corresponds to the cost estimates in table 4. Infrastructure along the track requires an investment of 23,842 MNOK, and safety-related infrastructure at stations accounts for 2,749 MNOK. Additionally, onboard safety equipment is estimated at 900 MNOK. These costs are only included for alternative C. The final expected cost is 34,296 MNOK, significantly higher than for alternative A and B, and in practice a showstopper for this alternative.

Concept C contains several additional systems beyond ATO to ensure that safety is safeguarded. This also includes elements with a much lower maturity than concepts A and B, while having assumed separate risk assessments due to the immaturity of GoA3/4 standards and technology. Hence, the considerations this far is rather a safe side judgement implicating high efforts and costs. Consequently, the cost for alternative C includes investments for safety improvements, such as fencing along the line, removing level crossings and installing platform screen doors on stations. These measures have significant additional costs compared to the other alternatives. Further developments will most likely better show what will really be the required safety measures to implement GOA3/4 driving. Alternative C was also studied in some variants, including only using ATO on the most congested lines, which are urban commuter lines in main cities.

4.2.2 Benefits from ATO and socio-economic analysis

To estimate benefits from ATO, simulations are done for punctuality, headway and energy use. Headway simulations are only done for double tracks. The headway simulations indicate a possibility for reducing headway by 2 to 4%, and this applies to all alternatives. Punctuality has been analyzed for different parts of the railway network, and for rush-hour and non-rush-hour traffic. The reduction in energy use varied from 0 change for local trains to up to 3% reduction for freight trains, with an average of 2% reduction.

Table 5 shows the average expected punctuality improvements for the different alternatives.

Different socio-economic calculations have been made for either optimizing energy use or optimizing capacity use. The options for optimization for capacity have a higher socio-economic value for all of the main alternatives, compared to optimizing for energy use. Only alternative A, with driver support aimed at increasing capacity, gives a positive net present value and is consequently a socially profitable investment. This alternative can also serve as a first step in the development towards a solution where ATO is put into use on the Norwegian railway network.

Table 5 - Summary of estimated benefits (in 2023 NOK)

	Alt A	Alt B	Alt C	Alt C1
Concept	C-DAS	GoA2	GoA3 all Norway	GoA3 Oslo area
Cost (MNOK)	1 100	2 300	34 300	3 000
km railway	4 500	4 500	4 500	200
cost/km (MNOK)	0,2	0,5	7,6	15,1
Reduced delays (%)	20	19	28	25
Improved punctuality (%)	2	2	3	3
Headway reduction (%)	3	3	3	3
Energy use reduction (%)	-1.5	-1.5	-1.5	-1.5
Net present socio economic v	2 123	-6 047	-10 493	-23 774
Estimated (cost/km)/capacity increase in %	0,08	0,17	2,54	5,02
Estimated (cost/km)/punctuality increase	0,12	0,27	2,76	6,02
Estimated cost/capacity increase in %	367	767	11 433	1 000
Estimated cost/punctuality increase	556	1 232	12 398	1 200

The study has commented that the effects on society of technological projects are difficult to identify and analyze using existing analytical tools, which are largely aimed at traditional infrastructure investments, such as expanded capacity on existing lines.

5. Discussion and applying the KPIs

Our comparisons between infrastructure and ATO will focus on the expected situations, because we do not have data on the “after” situation for ATO as it has not happened yet. Table

3 also enables us to compare the expected and actual situation after project implementation, which we will return to.

Because tables 3 and 5 contain only a limited number of measurements, covering four ATO concepts and six major infrastructure projects, the comparison focuses on the highest and lowest values within each category to provide an indication of the overall scale and range.

To begin with, table 6 uses the KPI cost per kilometer, seen in relation to the percentage change in capacity and punctuality. Such a KPI is not easy explained. However, cost per kilometer is an established metric at least for infrastructure investments, and using change in percent enables us to compare, or at least get on indication, of capacity change even if the infrastructure projects and the ATO analysis have used different capacity metrics.

Table 6 - Using cost/km in relation to capacity and punctuality increase. Based on expected values, from front-end analyses of infrastructure and ATO investments.

	Cost/km/ additional train		Cost/km/ Capacity increase		Cost/km/ Punctuality increase	
	High	Low	High	Low	High	Low
Infrastructure	117	6	2 343	180	85	36
ATO			5,02	0,08	6,02	0,12

The results show a difference of roughly three orders of magnitude between infrastructure and ATO in cost per kilometer for capacity improvements, suggesting that cost/km is not a suitable indicator for this type of comparison, even if it is commonly used for infrastructure projects. For punctuality improvements, however, the difference is closer to a factor of 10, which makes the comparison more meaningful and points to ATO as relatively cost-effective. Among the alternatives, ATO GoA3 or GoA4 around Oslo is the most comparable option in scale to infrastructure projects. Although it is the most expensive per kilometer of the ATO concepts, it may still be considered cost-effective relative to capacity and infrastructure investment.

Table 7 uses cost for the total projects, while the change in capacity and punctuality is measured in the same way as in table 6, as percentage change.

Table 7 - Using cost in relation to capacity and punctuality increase. Based on expected values, from front-end analyses of infrastructure and ATO investments.

	Cost/ additional train	Cost/ Capacity increase	Cost/ Punctuality increase

	High	Low	High	Low	High	Low
Infrastructure	1 307	133	223	23	809	363
ATO			11 433	367	12 398	556

When costs are considered at the project level, without adjusting for the length of line affected, the results for infrastructure and ATO may become more directly comparable. Infrastructure cost is highly influenced by the length of the line affected. The ATO investment is only partially a function of line length involved, even though the strong focus on safety measures are depending on what part and size of the railway network where ATO is considered to be applied in the study. Implementing full ATO GoA3 or GoA4 across the entire Norwegian network would incur very high costs relative to the improvements achieved, performing worse socio-economically than other ATO alternatives. However, large-scale infrastructure upgrades across the whole network would also be extremely costly if analyzed in the same way. The analysis suggests that, for achieving capacity or punctuality improvements on specific sections of a railway network, traditional infrastructure investments are currently more cost-effective than ATO at the assumed cost levels. While infrastructure costs are substantial, ATO costs remain highly uncertain, reflecting the technology's immaturity on mainline routes.

Infrastructure and ATO are not mutually exclusive. Infrastructure investments can drive major capacity increases, for example, the Sandnes-Stavanger project demonstrates that converting single-track lines to double track can double capacity, while ATO alone is unlikely to achieve such gains. In terms of punctuality, both approaches offer comparable improvements, typically within a few percentage points, suggesting that combining infrastructure and ATO could optimize both capacity and reliability.

In brief, the performance of the infrastructure projects has been assessed in previous studies (Concept, 2025), although cost ratios are not typically included in such evaluations. Our analysis indicates that the cost per additional train varies widely, ranging from as low as 111 MNOK to approximately 4000 MNOK, and in some cases, no immediate increase in capacity is observed shortly after opening new infrastructure. As noted by Olsson (2006), the timing of these evaluations has a significant impact on the results. Railway investments are highly sensitive to whether timetables have been adjusted to fully exploit the theoretical capacity increases provided by the new infrastructure.

When comparing expected and actual values for the infrastructure investments, we may note that cost performance is rather good, with average cost per kilometer below the expected. This is partly depending on the selection of projects and not adjusted for relative size of projects, but in accordance with previous studies of large governmental projects in Norway (Concept, 2025). However, the actual frequencies are close to only a third of the expected. This means that the cost per train is much higher than expected. A key reason for this is that the frequency on a train line is governed by the timetable, not the available capacity on a new line. For many of the projects studied, timetable changes came later than the cut off time for evaluations (typically two years after opening of new infrastructure). This is in accordance with previous studies such as Olsson (2006).

Table 8 – Comparing average values for expected and actual situation after infrastructure investments.

Average values	Punctuality	Frequency change	Cost/km (MNOK)	Cost/train (MNOK)
Expected	95%	82%	485	720
Actual	93%	20%	446	2592

6. Conclusion

This paper has developed and tested a framework for systematically comparing the costs and benefits of traditional railway infrastructure investments and Automatic Train Operation (ATO). The framework is built around key performance indicators (KPIs) that link investment costs, measured both as cost per kilometer and as total project costs, to two comparable benefits: capacity (in terms of additional trains or frequency increases) and punctuality improvements. These relationships are captured through cost–benefit ratios such as cost per additional train, cost per capacity increase, and cost per punctuality increase. By applying the same indicators to Norwegian infrastructure projects and ATO concepts, the framework enables a structured assessment of relative cost-effectiveness and clarifies where one type of intervention offers advantages over the other.

The analysis shows that cost-effectiveness varies depending on the metric. On a cost-per-kilometer basis, ATO appears more cost-effective than infrastructure projects for punctuality improvements but less suitable for capacity gains due to differences in scale. When using project-level costs, the comparison becomes more balanced, though some ATO concepts, particularly GoA3 or GoA4 applied to the whole network, performed poorly in socio-economic terms. By contrast, targeted deployment of ATO on smaller, dense sections, such as around Oslo, appears both more feasible and potentially competitive with infrastructure projects. The review of actual outcomes from infrastructure investments further underscores the difficulty of relying only on estimated figures: cost per additional train varied widely depending on contextual factors such as timing and timetable adjustments. Overall, the framework suggests that infrastructure remains the more reliable and cost-effective option for large-scale capacity improvements, while ATO offers potential for punctuality gains and incremental efficiency, especially as costs become clearer and technologies mature. Rather than being substitutes, infrastructure and ATO should be seen as complementary, with infrastructure providing capacity foundations and ATO enhancing reliability and resilience.

Theoretically, this research contributes to the literature on railway project evaluation by operationalizing a KPI-based framework that integrates economic efficiency with operational performance. While previous studies have highlighted the transformative effects of rail on accessibility, regional productivity, and economic development (Lucas et al., 2016; Cascetta et al., 2020; Kim and Sultana, 2015; Hong et al., 2011), as well as the persistent risks of cost overruns and inaccurate demand forecasts (Flyvbjerg, 2007; Vickerman, 2018), few have provided a structured approach to directly compare conventional infrastructure with digital automation. By narrowing the focus to capacity and punctuality, the framework addresses calls for more context-sensitive and multidimensional evaluation metrics in transport infrastructure (Fagerhaug and Olsson, 2005; Volden, 2018; Love et al., 2017).

Practically, the framework offers policymakers and railway planners a transparent tool for evaluating trade-offs between infrastructure upgrades and ATO. The findings indicate that while large-scale infrastructure investments are better suited to transformative capacity expansion, ATO may be more effective in delivering punctuality improvements and incremental operational efficiencies, particularly in high-demand corridors. This aligns with evidence that project success is highly dependent on geographical and operational context (Surmařová et al., 2025; Nyborg, 1998). Importantly, the framework highlights that infrastructure and automation can reinforce each other rather than compete, pointing toward integrated strategies for future railway development.

Looking ahead, the framework should be refined to incorporate a wider set of benefits, such as sustainability, safety, and broader socio-economic effects, and to account for the current uncertainty in ATO cost estimates. Empirical evidence from mainline ATO implementations will be especially valuable for strengthening comparative analyses. By building more robust and standardized KPIs, future research can better support decision-makers in designing cost-effective, sustainable, and context-appropriate strategies for improving railway performance

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