Trønderbanen Regional Rail 2024 Plan – Using Simulation to Optimize Infrastructure Investment

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Abstract
Travel demand in the Trondheim region of Norway is growing and the government wants to encourage use of sustainable transport modes. The area's Trønderbanen regional rail service is well used, but the line is operating near capacity and therefore new capital improvements are needed to increase service. This paper describes how railway simulation was used to help develop an optimized infrastructure investment plan for the railway as part of the Trønderbanen Regional 2024 Plan.

Keywords
Railway Scheduling, Timetables, Stochastic Simulation, Trønderbanen, Trondheim, Norway

1 Introduction

This paper describes how simulation was used to help develop the Trønderbanen Regional 2024 Plan being prepared by the Norwegian Railway Directorate (Jernbanedirektoratet). The plan seeks to significantly increase regional rail service around Trondheim, Norway's third largest city, and introduce a regular interval timetable.

The Trondheim region is located along the Trondheim Fjord about 500 km north of Oslo. Since the area is highly mountainous, most of the region's 293,000 residents are settled in valleys and along the coast and fjords. This topography makes the area ideally suited for regional railway service.

The Trønderbanen service operates on tracks shared by national and international passenger and freight trains. As shown in Figure 1, there are three regional lines in the Trondheim area. The Trønderbanen line is R26 (Lundamo/Melhus-Steinkjer). The two other regional lines are RD25 Røros-Trondheim and RE72 Heimdal-Storlien. These regional lines overlap with line R26 and operate as part of the Trønderbanen in the Trondheim area. In addition, there are two long distance passenger trains FJ21 and FJ71 which operate on the same track network.

Existing Trønderbanen ridership is approximately 5,800 per weekday and about 1.6 million per year. Service operates about hourly from 5:00 am to midnight with additional peak period service. There are approximately 30 trains per day and direction on weekdays, and 15 on weekends.

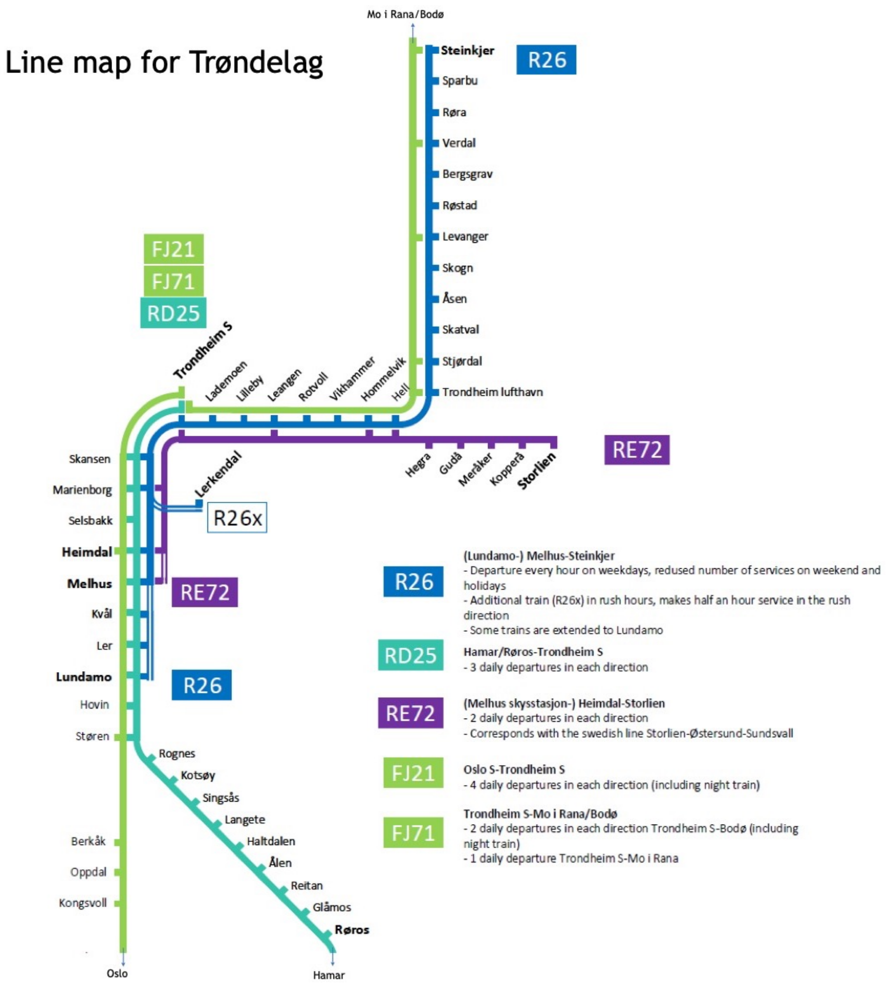

Figure 1 Schematic diagram of Trondheim area railway service.

The Trønderbanen Regional 2024 Timetable Planning Study was completed by Trenolab. The study developed and evaluated alternative timetables designed to achieve the service objectives (30-minute frequency regular interval timetable) and identified the infrastructure needed to operate them. Jernbanedirektoratet used the study to help develop a long-term infrastructure plan for the Trønderbanen, including the important decision about electrification of the line linking Trondheim to Steinkjer and Storlien. (NRD, 2019)

2 Timetable Planning Study Objectives and Methodology

The Jernbanedirektoratet's goal of providing 30-minute service between Trondheim and Steinkjer throughout the day was used to create objectives for the future timetables. These objectives were to provide: (1) a regular-interval structure, (2) the shortest possible running times, and (3) minimize the need for new infrastructure. Short running times and a regular-interval structure increase the attractiveness of the service for passengers, while using the existing infrastructure reduces capital costs and increases efficiency.

It was difficult to create timetables that met all three objectives given the Trønderbanen network's long single-track sections, high service density and broad mix of services. Therefore, planners used simulation to evaluate trade-offs between these objectives.

Computers have been used for many years to support railway timetable planning: initially for simple tasks such as computing running times. Starting in the late 1980s macroscopic timetable planning software (e.g., Viriato (SMA, 2021)) was developed that supported high-level planning. By the early 2000s large scale microscopic simulation software supporting more detailed railway investment and service planning became available (e.g., OpenTrack (Nash and Hurlieman, 2004), and RailSys (rmcon, 2021)). This is well described in (Zinzer et. al. 2018, and Medeossi, 2018) and is not repeated here.

The rapid improvement in computer processing power and development of new operations research techniques has led to the creation of new software tools and software-based timetable planning processes designed to make simulation efficient enough to be used throughout the planning process. More specifically, now simulation can be used to help develop and fine-tune timetable alternatives, rather than only for timetable validation at the end of the process. For example, trenissimo (de Fabris, 2018) the software used in this study is a microscopic, synchronous simulation tool; it uses a mixed continuous and discrete approach: continuous in solving the motion equation, and discrete in reproducing the signaling and interlocking systems. trenissimo uses the latest software design practices (e.g., separation of animation and calculation, parallel processing, and high-performance computing) to significantly speed-up simulation. Furthermore, it is fully integrated with the timetable planning tool TRENOplus (which includes a macroscopic model) and the data analysis tool TRENOanalysis so it can be used in all three stages of planning: (1) analysis of current operations, (2) design of scenarios and (3) alternative testing (simulation). This integrated software approach significantly improves the timetable planning process.

In the Trønderbanen study the three tools were used to develop and evaluate alternative timetables (i.e., regular interval timetables with short running times to meet project objectives 1 and 2) and to identify infrastructure requirements (to help achieve project objective 3 of minimizing infrastructure). This approach combines the advantages of an efficient timetable planning tool (trains planned at macroscopic level) with the accuracy of microscopic simulation used to test changes. Figure 2 illustrates the project workflow.

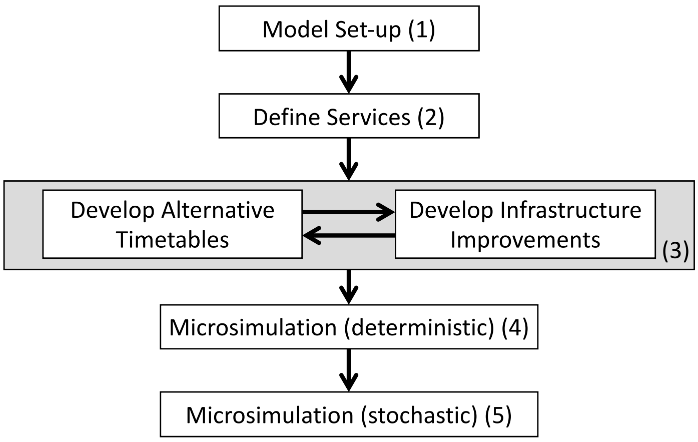

Figure 2: Trønderbanen Regional 2024 Timetable Planning Study Methodology

Step 1: Model Setup – This consists of creating the macroscopic and macroscopic models being used in the planning study. The models are created by entering appropriate level infrastructure and operating data into the models. This data was already available for both models from the Norwegian National Infrastructure Model.

Step 2: Define Services – This consists of entering the train service definitions needed to meet the desired service objectives listed above into TRENOplus. These definitions describe the frequency, stopping pattern, stop times, and the rolling stock. The train running times were calculated using TRENOplus on the microscopic model.

Step 3: Develop Alternative Timetables and Infrastructure Improvements – Developing timetables is an iterative process consisting of creating timetables, testing them, and refining them to reduce conflicts. Where conflicts occur infrastructure is needed (e.g., passing tracks), or the timetable must be adjusted so that the trains meet in a location that already has passing tracks. Of course, these timetable adjustments will change where trains meet at other locations on the line.

The process for creating a timetable begins by inserting the highest priority trains into the TRENOplus timetable planning tool. The tool will quickly plot the train paths on a time space diagram according to user-specified rules (e.g., train priority). Planners can review this timetable and edit it to better meet study objectives by making adjustments such as those listed in Table 1 – all directly within the tool. Once an acceptable timetable has been created for the high priority trains, additional trains can be added following the same process until all the trains have been inserted.

Table 1: Train adjustment strategies for timetable development

Adjustment	Description	Trade-offs
Departure adjustments	Adjusting the time when a train departs a station changes the crossing locations.	RIT problem – esp. bad when trains leave earlier.
Skip station stops	Reduces travel time and therefore changes the crossing locations.	Reduced service to skipped stations + RIT problem.
Add stations	Increases travel times and therefore changes the crossing locations.	Slower travel times.
Change insertion order	Different way to develop timetable: start by inserting train type B rather than type A.	None
Short turn trains	Changes crossing locations and can also eliminate crossings.	RIT problem + benefit of making rolling stock available for earlier trips.

RIT = Regular interval timetable problem: Adjusting individual trains in a regular interval timetable changes the pattern and therefore reduces customer friendliness.

Often a timetable is developed first for a several-hour reference period (called BUP – Basic Hour Pattern). This accelerates the process of identifying a limited set of reasonable alternatives by helping planners quickly define and test alternatives. These alternatives are then used to create 24-hour timetables by repeating the BUP and then adding the less frequently operated trains (i.e., long-distance passenger and freight trains).

Timetable planning tools improve the efficiency of this process by allowing planners to quickly adjust timetables (e.g., by moving train graph string lines on time space diagrams displayed on the computer screen) and immediately see the conflicts in the new timetable.

The result of this step is a set of alternative timetables with data describing their performance (e.g., travel times, new infrastructure requirements).

Step 4: Test Alternative Timetables with Microsimulation (Deterministic) – The timetable alternatives are tested using the microscopic simulation model to determine their feasibility. In this step the microsimulation model is run deterministically (i.e., assuming no delays). If the timetable is found infeasible, step 3 is repeated until a feasible timetable is found.

Step 5: Test Alternative Timetables with Microsimulation (Stochastic) – Here the timetable is simulated multiple times with each simulation containing variations in the departure and dwell times (i.e., delays) based on actual operating statistics. This provides a preliminary evaluation of timetable robustness – how well the timetable can recover from disruptions.

The methodology presented above was followed to develop alternative timetables for the Trønderbanen Regional 2024 Plan. A report was prepared describing study results and recommendations. During 2018 Jernbanedirektoratet used the timetable study results together with infrastructure feasibility and cost studies to make a series of service and infrastructure planning decisions.

In 2019, the process was repeated to develop a new timetable and assess infrastructure requirements consistent with Jernbanedirektoratet's service and infrastructure decisions. This revised analysis could be completed quickly using the existing mesoscopic tool and microsimulation model. The rest of this paper describes how the methodology described in this section was used in the initial and revised studies.

3 Timetable Alternative Development and Testing – Initial Study

The first step in the timetable analysis was to create and prepare the models using future assumptions regarding service objectives, infrastructure and operating data.

The Jernbanedirektoratet is planning many capital investments on the study area lines. These include increasing terminal capacity at several terminals, installing or lengthening crossing loops in several locations, installing the European Traffic Control System (ETCS) on the lines from Trondheim to the Swedish border and Bodø, electrification from Trondheim to the Swedish border and to Steinkjer, and double tracking the segment Hell – Værnes. The ETCS project will include a new train management system (TMS) and centralized train control where it does not yet exist.

The analysis assumed that the latest generation of rolling stock would be used for each type of train. Regional trains will be operated with Flirt multiple unit trains, long distance passenger and freight trains will be operated by with locomotive and wagons. Rolling stock performance data including a power/weight ratio of 7 kW/Ton and 100 km/h maximum speed for freight trains were used in the analysis.

As mentioned above, the Jernbanedirektoratet's objective was to increase the frequency of service and reduce travel times. The frequency objectives are presented in Table 2.
The Jernbanedirektoratet's travel time goals for regional trains were defined as:

- R 64: 54 minutes: Trondheim – Støren;
- R 66: 26 min.: Trondheim–Melhus Skysstasjon; 97 min.: Trondheim– Steinkjer;
- R 67: 7 min.: Trondheim – Marienborg; 31 minutes: Trondheim – Stjørdal.

Finally, the initial analyses assumed a fixed dwell time of 40 seconds for regional and 60 seconds for long-distance trains.

Table 2: Frequency objectives

Line	Endpoints	Tr. type	Rolling Stock	Frequency
R 64	Trondheim-Røros	Regional	BM 93-E	3 TPD
R 66	Steinkjer-Søberg/Lundamo	Regional	BM 75-E	1 TPH
R 67	Stjørdal-Lerkendal	Regional	BM 75-E	1 TPH
R67e	Stjørdal –Steinkjer	Regional	BM 75-E	1 TPH
F 61	Trondheim-Støren (Oslo)	Passenger	EI 18 + 4xB7 + 3xWLAB, 160 km/h	4 TPD
F 71	Trondheim-Steinkjer	Passenger	CD 312 + 5xB5 + 2xWLAB, 160 km/h	3 TPD
F 72	Heimdal-Storlien	Passenger	BM 75-E	2 TPD
G 60	Trondheim-Støren (Oslo)	Goods-combi	EI 19, 600m, 800t, 100 km/h	8 TPD
G 70	Trondheim-Stod	Goods-combi	CD 312 600m, 800t, 100 km/h	2 TPD

TPD = Trains per day; TPH = Trains per hour; t = tons; km/h = kilometers per hour; Passenger trains are long distance.

In the second step, the input assumptions outlined above were used to create a microsimulation of the network with trenissimo and the TRENOanalysis timetable planning tool was adjusted to be consistent with model minimum travel time results.

Next alternative timetable scenarios could be developed. This started by inserting the highest priority train type into a blank timetable grid in TRENOanalysis, adjusting the specific times if necessary, and then inserting the next priority train type. A BUP timetable was created and expanded into a 24-hour timetable.

As more trains are added to the timetable the timetable adjustment strategies listed in Table 1 above were used to reduce the impact of crossings on travel times. In other words, it may be necessary to shift a departure time for a regional train slightly to eliminate the need for a long-distance passenger train to wait on a passing track.

During the initial study 5 timetable scenarios were developed and tested. All scenarios had the same number of trains. New scenarios were developed by closely analyzing the results of previous scenarios and developing strategies for addressing the identified problems. These scenarios and key results were:

- ***Scenario 1-A:*** train insertion priority: R-66 (longest distance), R-67, R-64, long-distance passenger, and freight trains; key result: very long waiting time at some crossings meant that travel time objectives were far from being met (R-66 takes 124-minutes compared to goal of 97-minutes) and very little residual capacity.
- ***Scenario 1-B***: train insertion priority: R-66, long-distance passenger, freight, R-67, R-64; key result: travel time objective for R-67 could not be met without substantial infrastructure requirements.
- ***Scenario 2:*** infrastructure: extension of passing tracks at 2 stations; headway of R-66 reduced from 60- to 40-minutes, R-67 service reduced; train insertion priority: R-66, R-67, long-distance passenger, freight; key results: good travel times, limited residual capacity, large number of skipped stops for R-67 service.
- ***Scenario 3***: infrastructure: two new crossing points and a double track extension; train insertion priority: R-65, R-67, long-distance passenger, freight, R-67e; key results: good travel times, limited residual capacity, fairly high infrastructure costs.
- ***Scenario 0***: existing service with R 2027 infrastructure and rolling stock assumptions; train insertion priority: R-66, R-67, R-64, long-distance passenger,

freight; key results: good running times, but service increase consistent with Trønderbanen objectives was not possible.

After this initial analysis, all scenarios except 1-B were analyzed in more detail using microscopic simulation.

Microscopic simulation is a powerful tool used to analyze railway timetables by modelling the rolling stock, infrastructure and timetable, as well as, most importantly, the constraints that trains place on each other when operating over the same infrastructure. Microscopic simulation is used to assess timetable feasibility and robustness.

Robustness is the ability of a railway timetable to recover from a disruption. It helps show how delays propagate through the network. When robustness is high (good) the trains return to running on schedule quickly, when robustness is low the trains take a long time to return to running on schedule. Logically there is an inverse relationship between capacity and robustness: railways operating near full capacity have timetables that are generally less robust because there is less margin for trains to catch-up without affecting other trains.

The study used microscopic simulation to examine the four scenarios in the following three ways:

- ***Deterministic simulation*** – assumes that there are no delays and all trains operate precisely on schedule; deterministic simulation can be used to model train operations more precisely than is possible using mesoscopic tools, and therefore provides an important check on the alternative timetables.
- ***Deterministic "plus" simulation*** – adds a small amount of time to the route release time assumed in the microscopic simulation model, thus increasing the block occupation times. This provides a simple test of timetable robustness.
- ***Stochastic simulation*** – considers the variability of parameters that can be statistically modelled such as station dwell time or departure delay. A stochastic simulation is performed by repeating a simulation with varying parameter values (statistically defined) for a statistically significant number of iterations (each iteration is a virtual operating day). In this study the departure time was chosen for analysis and modelled using a negative exponential distribution with a mean of 2-minutes, which is a bit higher than the actual value of 80-seconds. Stochastic simulation provides a very detailed analysis of timetable robustness.

Results of the microscopic simulation and mesoscopic analyses are presented in Table 3.

Table 3: Timetable alternative evaluation Trønderbanen Regional 2024 Plan (1).

Criterion	**Scenario 1A**	**Scenario 2**	**Scenario 3**	**Scenario 0**
Short running time goal	Poor	Good	Good	Good
Meets frequency goals	Yes	Yes	Yes	No
Infrastructure costs	Zero	High	Medium	Zero
Deterministic analysis (2)	Good	Satisfactory	Good	Good
Deterministic + anal. (2)	Satisfactory	Unsatisfactory	Good	Very good
Stochastic analysis (2)	Very good	Unsatisfactory	Good	Very good

(1) Relative assessments of timetable quality by Jernbanedirektoratet and consultants.
(2) Difference between planned timetable and modelled operating results.

The Jernbanedirektoratet used the study results to refine their service objectives and infrastructure planning. The next section describes these decisions and how the timetable analysis study was extended to develop and analyze a new set of timetable alternatives consistent with these decisions.

4 Timetable Alternative Development and Testing – Revised Study

The Jernbanedirektoratet made several infrastructure and service decisions for the Trønderbanen Regional 2024 Plan based on the timetable study results presented above and other analyses. Most important for purposes of the refined timetable analysis study were:

- Electrification – the full line to Steinkjer would not be electrified, but partial electrification (Trondheim-Stjørdal and on the Meråker line) should be considered.
- Crossing point location – the Jernbanedirektoratet provided precise guidance for crossing locations based on preliminary engineering studies.
- Service objectives – a new service plan was developed for the segment south of Trondheim. The new plan extended services to Støren by eliminating service to Lerkendal, increasing service and making it more regular.

The revised study's objective was to create and analyze reasonable timetable alternatives based on these decisions.

The study considered two alternatives: Alternative 1 assumed electrification between Trondheim and Stjørdal while Alternative 2 assumed no electrification of this line section. Both alternatives assumed that service would be operated with dual mode multiple units (Flirt BM-76 from Stadler). The BM-76 are similar to the BM-74/75 but are lower performance since they are heavier and generate less power in diesel than electric mode. Both timetables attempted to create an almost regular interval during the day, and to minimize the increase over technical minimum running time due to train crossings.

The study built on results of the earlier study and followed the same methodology. The study results compare the two electrification alternatives in terms of infrastructure needed, timetable robustness, and ability to meet service objectives.

The first step in the revised study was to develop travel times based on the new assumptions. As before the microscopic model was used to estimate these times. Next, planners created and analyzed the two alternative timetables. The key results were:

- ***Running time***: running time for regional trains in Alternative 1 is almost 10-minutes less than for Alternative 2 in both directions on the section north of Trondheim, but approximately the same in the section south of Trondheim where both alternatives operate with electric power.
- ***Residual capacity***: there was quite limited residual capacity for adding more trains in either alternative. Both alternatives use the capacity to a very high degree.
- ***Skipped stops***: Alternative 1 skips 5 stops in the section north of Trondheim while Alternative 2 only skips 2 stations (so Alt. 1 has a lower running time). Alternative 1 skips 1 station (and some trains skip two additional stations) in the section south of Trondheim, while Alternative 2 only skips one station on this section.
- ***Timetable adjustments impacting customer service***: In Alternative 2 it was necessary to replace one regional train in the southbound direction with a long-distance passenger train, increasing the passenger train's running time by about 15-minutes (13%) on this section. In Alternative 1 it was necessary to slightly adjust the regional train timetables with the result that they did not precisely follow the regular interval pattern and one of the regional trains needed to be turned back at Røra instead of Steinkjer.
- ***Rolling stock requirements:*** Both alternatives use 12 trainsets for operating the regional services between Steinkjer and Støren, with an additional 3 trainsets for operating the Røros services.

The main advantage of Alternative 2 is that it requires fewer infrastructure improvements than Alternative 1, and does not require electrification north of Trondheim.

In the revised study a robustness analysis was prepared for both new alternatives and the existing timetable (stochastic analysis only). The same approach was used for this analysis as for the original study (deterministic simulation, deterministic "plus" and stochastic), although the stochastic analysis was more detailed.

In this study, the stochastic simulations started with results from the deterministic simulation. Next, a complete set of dwell time distributions was applied to the simulations based on the stochastic input definition. The simulation was repeated 50 times for each alternative to obtain statistically significant results.

After running a first full set of 50 iterations, the graphic timetables were checked in order to detect and correct any deadlocks affecting the simulations. Next, the departure delay distributions were gradually inserted, starting with very tight distributions and progressively extending the distribution tails after solving any resulting deadlocks and major conflicts. The distributions were standardized and developed based on data from current train operations (R2016 TIOS data). The objective was not to consider the full distribution tails but to maintain the average mean delay.

Finally, train performance was also varied in the analysis. Here performance data was directly inserted into the simulation software. Train performance was based on train category varying between 90 and 98% for on time trains, and 94 and 98% for delayed trains. Results of the microscopic simulation and mesoscopic analyses are presented in Table 4.

Table 4: Summary results: Revised alternatives Trønderbanen Regional 2024 Plan (1).

Criterion	**Alternative 1**	**Alternative 2**	**Existing (R 2016)**
Short running time goal	Good	Satisfactory	
Meets frequency goals	Yes	Yes	Much less service
Infrastructure costs	Higher	Lower	
Deterministic analysis. (2)	Good	Good	
Deterministic plus anal. (2)	Good	Good	
Stochastic analysis (3)	Worst	Second best	Best performing

(1) Relative assessments of timetable quality by Jernbanedirektoratet and consultants.
(2) Difference between planned timetable and modelled operating results.
(3) Assessment based on non-negative mean delay and on-time train performance.

In this analysis the timetable robustness was assessed using the non-negative mean delay (M+) at all mandatory stops and the on-time performance (the percentage of trains arriving with less than 1-minute delay). The assessment was made for the R-66 trains on hourly time bands and considered the sections north and south of Trondheim separately. Table 4 presents a qualitative description of this assessment.

As shown in Table 4, Alternative 2 (non-electrified) performs better than Alternative 1 (electrified). This result is due to specific infrastructure-timetable combination and shows the benefit of simulation in timetable planning. Interestingly, the existing timetable appears more robust than either of the proposed alternatives due to significantly higher timetable margins, longer minimum stop times, better rolling stock performance and, less service.

5 Conclusions

The Trønderbanen Regional 2024 Plan study was completed in two parts. The first compared five timetable alternatives and was used by the Jernbanedirektoratet and Ministry of Transportation and Communications to make several decisions regarding rolling stock, service and infrastructure plans. The second part developed and analyzed two new timetable alternatives based on these decisions.

Two feasible and reasonable timetable alternatives were developed. Alternative 1, which assumes electrification of the Trondheim – Støren line creates a very tight timetable structure that leads to more attractive running times, but also requires more infrastructure improvements and skips more stations than Alternative 2. Alternative 2 (no electrification of the Trondheim – Støren line) is a less demanding timetable with longer running times but requires fewer infrastructure improvements.

A microscopic simulation demonstrated the feasibility of both timetables under realistic delay conditions but highlighted the lower robustness of both proposals compared to the current timetable. This is a result of the shorter running times, higher frequency service and lower performance of the new trainsets. As expected, the tighter Alternative 1 proved less robust than Alternative 2. In summary, both timetables meet the project requirements in terms of capacity and running times, while also offering regular-interval regional services.

This paper summarizes how timetable development and analysis were performed as part of developing a long-term master plan for regional railway service in the Trondheim region. A key goal is to illustrate how computerized analysis tools such as microscopic simulation and mesoscopic design and analysis tools can be effectively used in this process.

Simulation and mesoscopic tools have two main benefits. First, they enable planners to develop and test many different alternatives quickly and easily. It would be practically impossible to have been able to test the number of alternatives considered in this analysis without using these tools. (Note that many additional alternatives were tested and refined during this study to create the specific alternatives described in this paper.)

Second, these tools enable planners to quantitatively evaluate timetables in ways that are, again, practically impossible without computerization. For example, microsimulation enables planners to include interaction between trains and signaling systems in their analysis, and, stochastic simulation enables planners to consider real world operations.

In short, as in most fields, the rapid development of new information technology tools is creating the possibility for planners to vastly improve the quality of their plans and enables railways to develop efficient and attractive plans for their customers.

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