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The Resignalling Challenge: Investigating the Possibilities and Limitations of a New CBTC Signalling System on the Copenhagen Metro

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Abstract
This study explores the feasibility and advantages of implementing a Communications-Based Train Control (CBTC) signalling system on the Copenhagen Metro. As urban rail transit faces increasing passenger demand and the impending obsolescence of its current signalling system, CBTC emerges as a promising solution to enhance operational efficiency. Through microsimulation, the study compares the existing system with CBTC, focusing on key performance indicators such as headway adherence, running time reliability, and delay management. Results demonstrate that CBTC significantly improves service reliability, capacity, energy efficiency, and operational robustness. Additionally, the study identifies Vanløse station as a critical bottleneck in capacity utilization, which can be alleviated through CBTC deployment. This research underscores the potential of CBTC to transform urban rail systems, providing insights into its application in brownfield projects.

Introduction
The increasing urban density and consequently passenger demand is a widespread challenge in urban rail transit systems (Bernardino, et al., 2015; Gogola, Sitanyiová, Černický, & Veterník, 2018). This is both for the need for higher passenger capacity on board, but also for the generation of traffic perturbation at stops due to extended dwellings (Baali, Kuipers, & Coulaud, 2025; Buchunde, Saidi, & Ataeian, 2024; Kuipers, 2024). The Copenhagen metro has seen a steady increase in ridership since its opening in 2002, and with the life cycle of its signalling initially planned at 30 years (recently extended to 35 years), this system is soon reaching its replacement time (Østergaard, 2025). The approaching deadline provides both challenges and opportunities for the system. On the one hand, the 30-years technological progress provides more effective solutions than what was available in the 1990s, when the system was designed as the first fully automated rail born metro in the world. On the other hand, a brownfield project is subject to several constraints that are typically absent when designing new systems from scratch.

Extensive literature and industrial practice identify Communications-Based Train Control (CBTC) as the primary solution for capacity issues in high-density rail systems, especially in the moving block iteration, which allows for a reduction in headway and corresponding increase in transport capacity (UITP; Hofbauer & Sundaram, 2024; Georgescu, 2006; Chabanon, 2013).

Within a brownfield project, the requirements specification for the renewed systems needs to account for the constraints provided by the existing infrastructure and the subsystems that are not being replaced. For example, it is very unlikely for a signalling system replacement project to also introduce modifications of the line alignment, meaning that the line speed will rarely be improved under such projects. Likewise, some stations, especially where turnarounds are operated regularly, might be a bottleneck for the network capacity, due to the track layout and other technical constraints. The layout of such stations is seldom modified under resignalling projects, which limits the potential capacity benefit of the new signalling system.

The concept of rail capacity is variegated and interpreted in different manners in literature. Despite the common understanding of the general concept of rail capacity as the number of movements that can be operated in the time unit, it is hard to define what movements should be considered in the computation (Sameni & Moradi, 2022). This consideration varies across the subparts of the infrastructure and strongly depends on the specific movements that are considered. Line capacity is often addressed as the number of paths that can be planned or operated in one direction (double-tracked lines) or in both directions (single-tracked lines), which is, in turn, heavily affected by the type and homogeneity of the paths themselves (Abril, et al., 2008). Station capacity depends on the sequence of conflicting paths that are considered, on the stopping pattern and the direction of each path (Armstrong & Preston, 2017).

Metros and urban/suburban rail systems, however, are often characterized by a high degree of homogeneity, and the industrial practice is to describe the capacity of the whole systems or its shares by the minimum headway that can be reached, because the movements considered are uniform in characteristics (stopping pattern, direction, rolling stock, etc.) (Yung-Cheng, Yun-Hsuan, & Yi-Ju, 2015). Even though this approximation allows easier comparison among scenarios, it hides several aspects of the railway operations that are still critical for the realization of quality service. How the system absorbs normal variations of the process times (stability) and how it is affected by major disruptions (resilience) or how quickly it can return to normal operations (robustness) are all determining factors in the realization of reliable and attractive service.

This study focuses on the benefits of a new signalling system from the point of view of the Rail Operations. The service reliability improvement is investigated from different perspectives and quantified in different performance indicators.

Method

This study is based on microsimulation of rail traffic in the metro system in different scenarios. The purpose is to quantify the performance variation between the scenarios rather than their absolute level. The final desired absolute performances will be defined in the concept and detailed design phase, with more detailed information about the specific technology deployed.

The approach can be synthetized in the following steps:

- Baseline scenario model creation, calibration, and validation of the current infrastructure
- Generation of the variant scenario model: the signalling system is changed to mimic CBTC
- Simulation and comparison of the two scenarios
    - A series of schedules are deployed in the simulations with increasing capacity consumption, starting from the current schedule and reducing the planned headway in steps of 5s
- Sensitivity analysis to the variation of specific operational parameters
    - Realized dwell time delays increased proportionally to the scheduled dwell time in steps of 10 percentage points from +10% to 50%
    - Rolling stock performance is increased proportionally to the current scenario in two steps of 16% and 33%, corresponding to adding a motored axel or a whole motored bogie
    - Line speed is increased where allowed by the horizontal alignment from 80 km/h in two steps to 90/h and 100 km/h, respectively.

The microsimulation is based on the tool Trenissimo by TrenoLab (De Fabris, Medeossi, & Montanaro, 2018). The stochastic simulation is based on delay distributions introduced in two elements: running times and dwell times. The running time variability is accounted for by introducing a stochastic multiplier of the maximum acceleration and braking rates, cruising speed and a further multiplier to account for increased performance in case of delays. The dwell time is divided into a minimum, deterministic share, and a variable dwell time, while a stochastic departure inaccuracy is also introduced, representing the delays occurring after the passenger exchange is completed. Each simulation is run 250 times, corresponding approximately to the number of weekdays in a year. The overall simulation is focused on normal operations with minor perturbation. This is because major disruptions require manual dispatching and reorganization of the service, introducing too large uncertainty on the contour conditions. The focus of this study is primarily the change in the signalling system, whereas the traffic management part is left to further development.

Performance evaluation

The evaluation of the rail operations focuses on several aspects. The importance of a multiparameter evaluation is also highlighted in previous studies on the same system, which expressed the limitation of single-focus KPI frameworks (Cerreto, 2024). Purely headway-based performance indicators miss the travel time component and might be misleading in the quality of service, as a given frequency can be operated at different values of commercial speed. At the same time, purely travel-time performance indicators miss the waiting time aspect and information on the passenger capacity delivered. In this study, both headway and running time variations are considered in the performance evaluation.

Headway adherence

The regularity of headway indicates the share of departures delivered at the desired headway (same station and direction). This indicator is labelled Service Quality (SQ) in the remaining text and is calculated as percentage of realized headways shorter or equal to the planned headway, including a +20% tolerance.

Heatmaps are also utilized to qualitatively evaluate the distribution of headways deviations over time across simulation runs.

Running time reliability

The reliability of running times is calculated as relative extension of the realized running times from end to end, compared to the scheduled running times. These times exclude, therefore, the dwell times at the turnaround stations.

The distributions resulting from the stochastic simulations are represented by both the Mean and Max values recorded.

Delays

Even though the metro does not operate on a public timetable but on a headway plan, the simulation does run based on a schedule, with planned passing times at stations and timing points. This allows to measure delays as difference between realized and planned times. Absolute delays and delay propagation are therefore included in the analysis on a quantitative and qualitative evaluation.

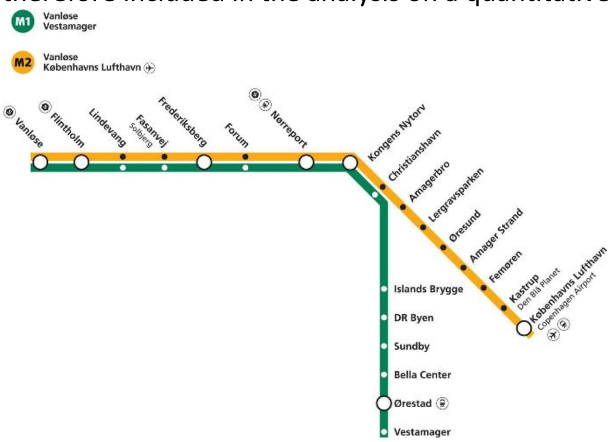

Figure 1 - Metro network schematics.

Table 1 - Station names and abbreviations

Name	Code	Metro Lines
Vestamager	VEA	M1
Ørestad	ORE	M1
Bella Center	BC	M1
Sundby	KHS	M1
DR Byen	UNI	M1
Islands Brygge	ISB	M1
Christianshavn	KHC	M1/M2
Kongens Nytorv	KGN	M1/M2/M3/M4
Nørreport	KN	M1/M2
Forum	FOR	M1/M2
Frederiksberg	FB	M1/M2/M3
Fasanvej	SOT	M1/M2
Lindevang	LIT	M1/M2
Flintholm	FL	M1/M2
Vanløse	VAN	M1/M2
Københavns Lufthavn	CPH	M2
Kastrup	KSA	M2
Femøren	FEO	M2
Amager Strand	AMS	M2
Øresund	OSV	M2
Lergravsparken	LGP	M2
Amagerbro	AMB	M2

Application: the Copenhagen Metro

This study examines the Metro Lines M1 and M2 in Copenhagen, which intersect between Vanløse and Christianshavn over nine stations before splitting towards Copenhagen Airport (M2, covering 7 stations) and Vestamager (M1, covering 6 stations).
The system operates in GoA4 (Unattended Train Operation) on a fixed block, track circuit-based distancing and signalling systems.
A basis scenario is modelled to represent the system as it is today as reference point.

New CBTC signalling system

A hypothetical CBTC system with moving block is introduced in this scenario. The infrastructure remains unchanged from the basis scenario, apart from these aspects:

- The legacy signalling system is replaced by a moving block CBTC, approximated as a ETCS L2-like system with virtual fixed blocks of length 20 m. This simplification is introduced to shorten the computational time in simulation and is deemed as not impacting the accuracy of the model (Hartmann, 2025).
- The technical dwell time at stations is reduced by 4 s. The communication between train and trackside is direct in a CBTC system, so the synchronization between train door and platform screen doors will expectedly be subject to shorter lags. The value is set at 4 s as the observed difference between the legacy system on M1/M2 and a CBTC-based system like M3/M4, with similar equipment as a side constraint.

New Rolling Stock

The renewal program for M1 and M2 includes a new fleet. The characteristics of the new rolling stock are still unknown, including information on traction and braking effort, empty mass, and motion resistance. The study considers, therefore, rolling stock equivalent to the current one, and evaluates the sensitivity of the results to traction effort changes. The current rolling stock is equipped with 3 motored bogies and 1 trailer bogie. Potential increases of motor power installed onboard are considered in a two-step approach, considering the same type of motors from the current trains, installed on one axle more or on one whole bogie more. This means that the rolling stock power considered is, referring to the current trains, equal, +1/6 (+16,6%), +1/3 (+33,3%).

Stochastic simulation: sensitivity analysis

The two signalling systems are compared in a sensitivity analysis of different performance indicators across 5 schedules representing the morning rush hour. The schedules are based on a planned headway of 95 s, 90 s, 85 s, 80 s, 75 s. Note that the schedules are realized only shifting the paths rigidly on the time scale, so the scheduled running times do not change between schedules.

Results and Discussion

Both deterministic and stochastic simulations were run on both the infrastructure scenarios for different investigations.
The simulations confirm that VAN acts as a bottleneck for the entire system. This is the terminal station of the common section of the network, where trains turn around on the shortest headway (Østergaard, 2025). The effect becomes more visible with shorter-headway plans. The capacity utilization here is heavily affected by the dwell times at the stations, which depends, in turn, on the assumed technical turnaround time of the rolling stock. This aspect should be investigated more in detail in future studies that also consider the traffic management systems logic. The station tracks and routes allocation becomes critical in this piece of infrastructure, as the minimum headway also depends on running time from station entrance to platform, and from platform to station exit. However, the impact of the VAN bottleneck changes between the signalling scenarios. In the current system, the delays accumulate in both directions TO and FROM VAN for 5 stations up to FOR. The estimated minimum feasible headway in the current scenario is 80 s. The CBTC scenario gains in reliability, capacity, energy efficiency, and robustness of operations. The specific evaluations for the different criteria are listed in the following sections.

The main difference between the legacy and the CBTC systems is a larger timetable slack in the latter, keeping the same schedule. This is due to both shorter occupation times in line (shorter reservation and release distance) and the larger recovery margin at dwell times due to the shorter minimum dwell time.

Operations stability against daily variations

The HW regularity indicator shows that standard operations are much more stable in the CBTC scenario, already in the 95 s HW scenario. This is also represented in the train diagrams in Figure 2. Here, the distribution of realized train trajectories is visibly closer to the schedule in the CBTC scenario. It must be noticed that much of this stability gain is linked to the reduction of minimum technical dwelling time.

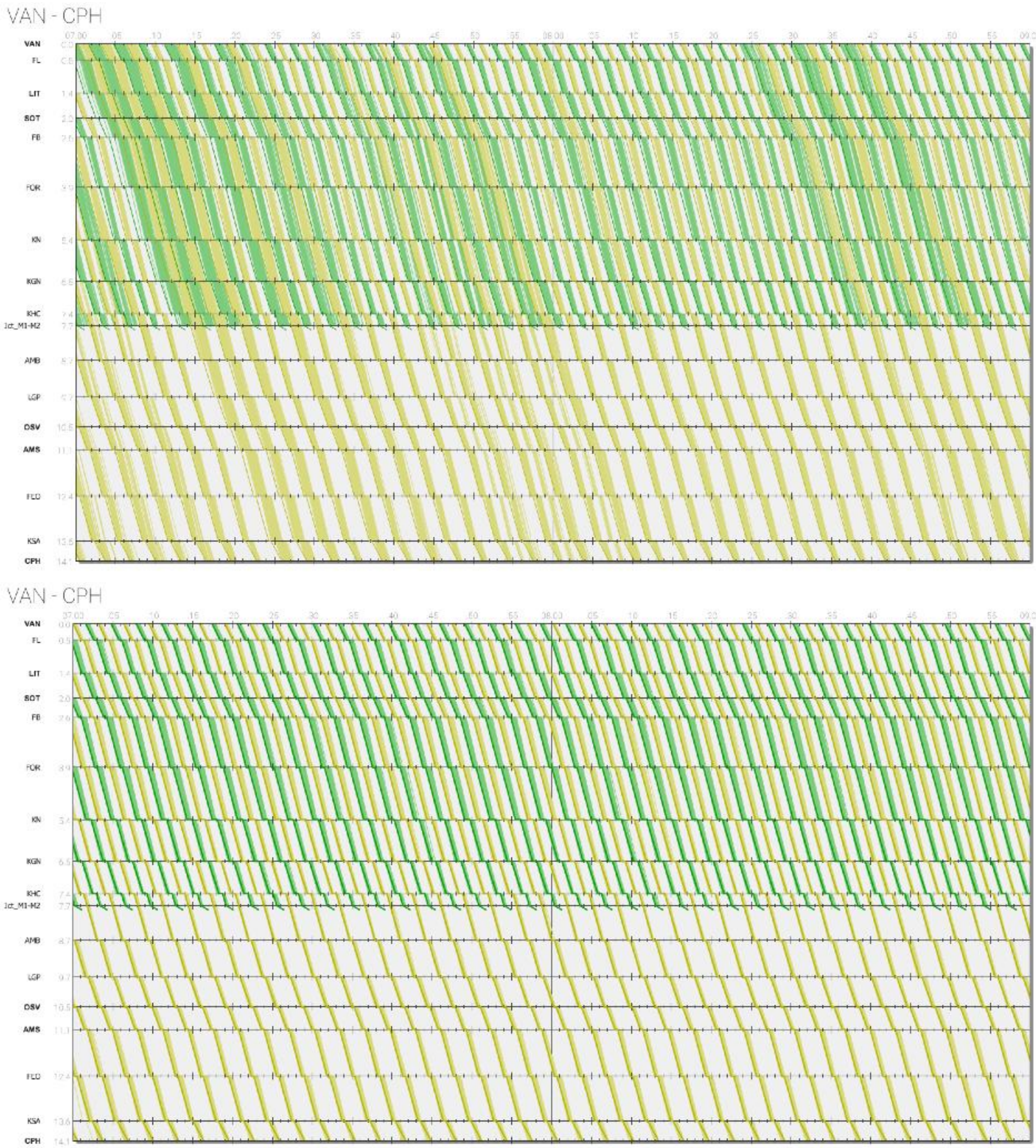

Figure 2 - Train diagrams of the stochastic simulations at 95 s HW. Top: legacy; Bottom: CBTC. Bold paths: schedule. The realized paths are stacked in transparency. Green paths: M1 VAN-VEA; Yellow paths: M2 VAN-CPH.

Figure 2 shows that the perturbations from the common section VAN-KHC, where the capacity consumption is much higher, propagate down to the branches (only KHC-CPH shown) in the legacy signalling scenario, whereas these can be recovered quickly enough in the CBTC before reaching the branching point. It is also noticeable that the distributions of trajectories in the time shrink down in the line in the CBTC scenario, meaning that perturbations are absorbed by the system. This is quantified in Figure 3, Table 2, and Figure 4. The Service Quality is kept higher in the CBTC scenario for all the service plans assessed, with a nearly linear slight decrease with the reduction of planned HW. On the contrary, the legacy system shows much lower values of SQ. The relationship with the planned HW is in this case clearly non-linear and requires some interpretation. Despite the value rising again after reaching the minimum value in the service plan at 85 s, the operations are not better in denser operations. This is the effect of all the trains queuing up after reaching the system's maximum capacity, as also visible by the running time extensions described in Table 2 and the delays depicted in Figure 4. Even in normal operations, service plans with 80 s and 75 s planned HW show an increasing delay during the simulation, meaning that the schedule cannot be followed by the trains due to capacity constraints. Noticeably, the running time extensions and delays are almost non-existent in all the service plans in the CBTC scenario.

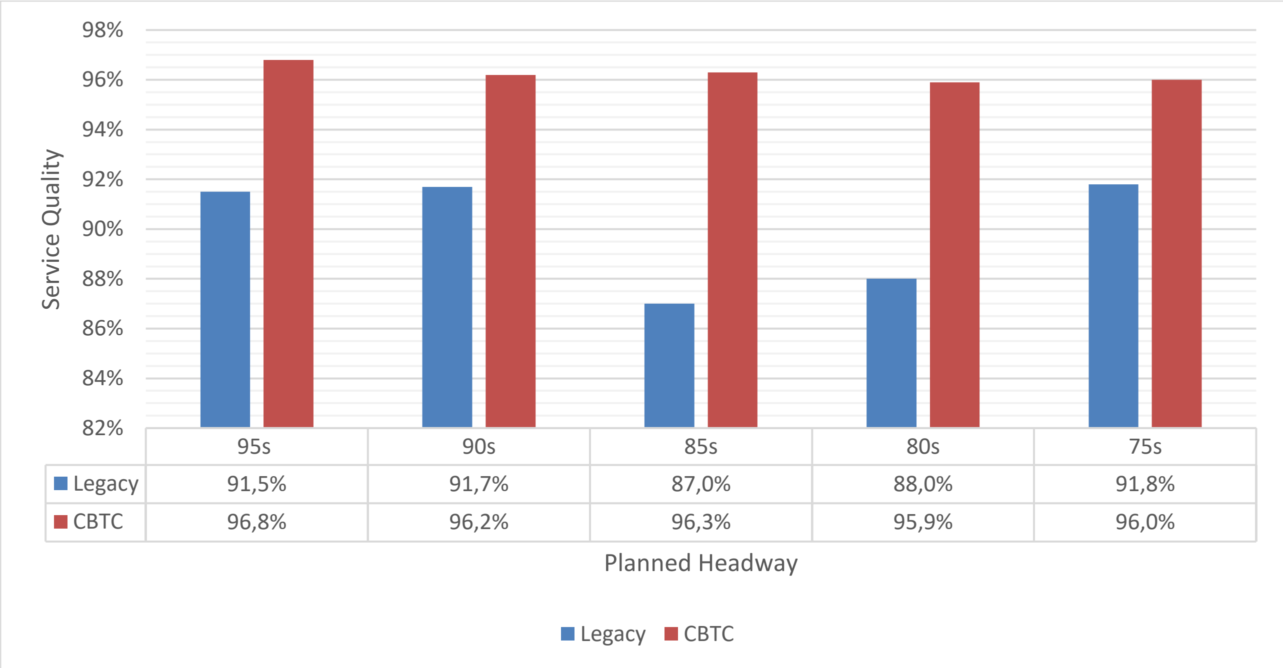

Figure 3 - Sensitivity of the Service Quality in the two infrastructure scenarios.

Table 2 - Running time extensions compared to the schedule.

Planned HW (s)	Scenario	CPH-VAN		VAN-CPH		VAN-VEA		VEA-VAN		Overall	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
75	Legacy	5%	7%	8%	12%	8%	11%	4%	6%	6%	12%
	CBTC	1%	2%	0%	0%	0%	0%	1%	5%	1%	5%
80	Legacy	3%	6%	1%	4%	0%	3%	4%	5%	2%	6%
	CBTC	0%	2%	0%	0%	0%	0%	0%	1%	0%	2%
85	Legacy	2%	4%	0%	5%	0%	4%	3%	5%	1%	5%
	CBTC	1%	1%	0%	0%	0%	0%	0%	2%	0%	2%
90	Legacy	3%	5%	0%	1%	0%	0%	2%	4%	1%	5%
	CBTC	1%	1%	0%	0%	0%	0%	1%	3%	0%	3%
95	Legacy	2%	4%	0%	0%	0%	0%	2%	4%	1%	4%
	CBTC	0%	1%	0%	0%	0%	0%	1%	1%	0%	1%

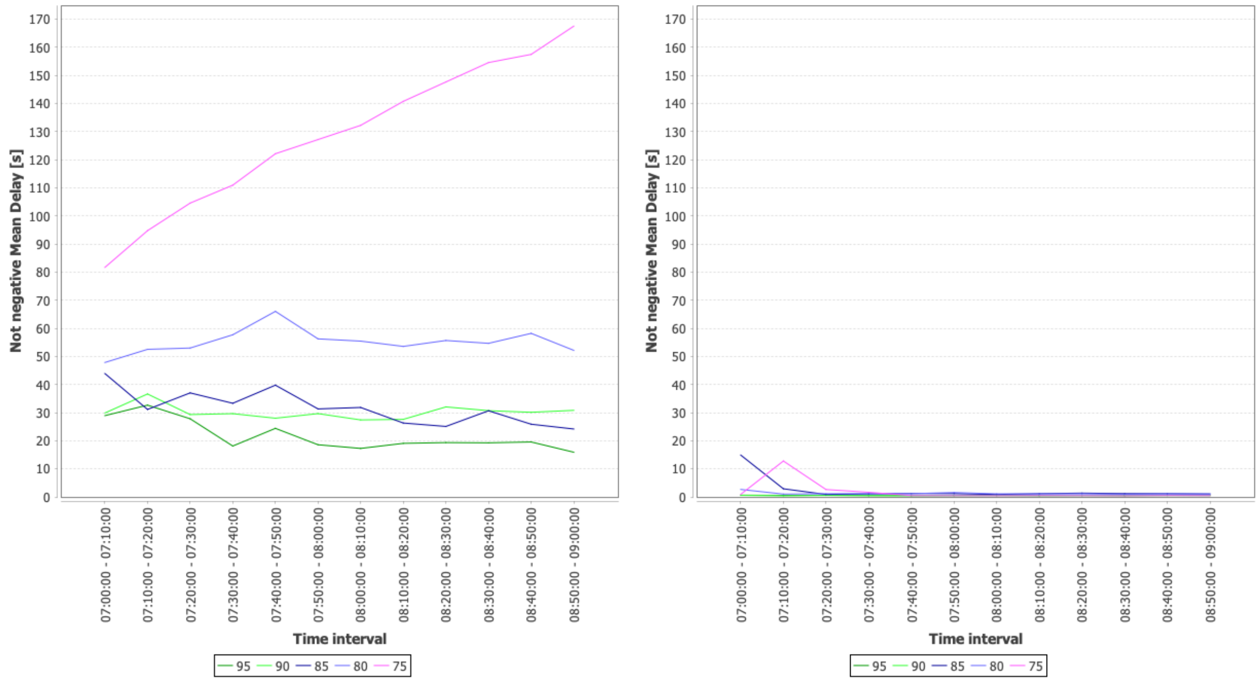

Figure 4 - Sensitivity of the running non-negative delays for the Legacy (left) and CBTC (right) systems. Each line represents one service plan based on the indicated HW.

Robustness of operations against larger perturbations

The positive effects of the reduced capacity consumption are also visible when considering large perturbations and the time it takes to return to normal operations. The example in Figure 5 shows a major perturbation taking place at FB at 7:00 and its propagation in the two systems. With reference to the network critical point of the Christianshavn junction, it takes 11 minutes from the first perturbed train to the first train running again in its designated path. The CBTC scenario improves this time to just over half, 6 minutes, with 4 trains fewer to be affected by the perturbations and fewer departures disrupted.

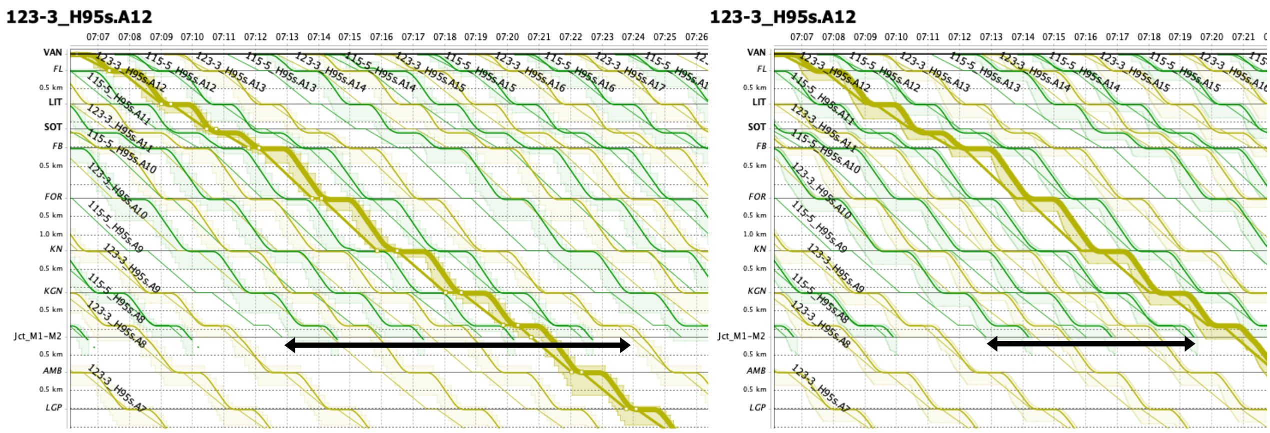

Figure 5 - Delay recovery time comparison. Left: Legacy system; Right: CBTC.

The general phenomenon is shown in Figure 6. Here, the propagation of the perturbation is visible in the Legacy signalling. Red dots indicate trains that were delayed, so their headway to the previous departure is longer than planned. The figure shows measurements from KN in the direction from VAN, so only perturbations occurred just before KN are clearly visible. In the legacy system, the red dots are followed by a series of up to 5 other trains running at shorter HW than planned, meaning these are running bunched. The CBTC scenario depicts much smoother operations, with milder HW deviations and very little bunching.

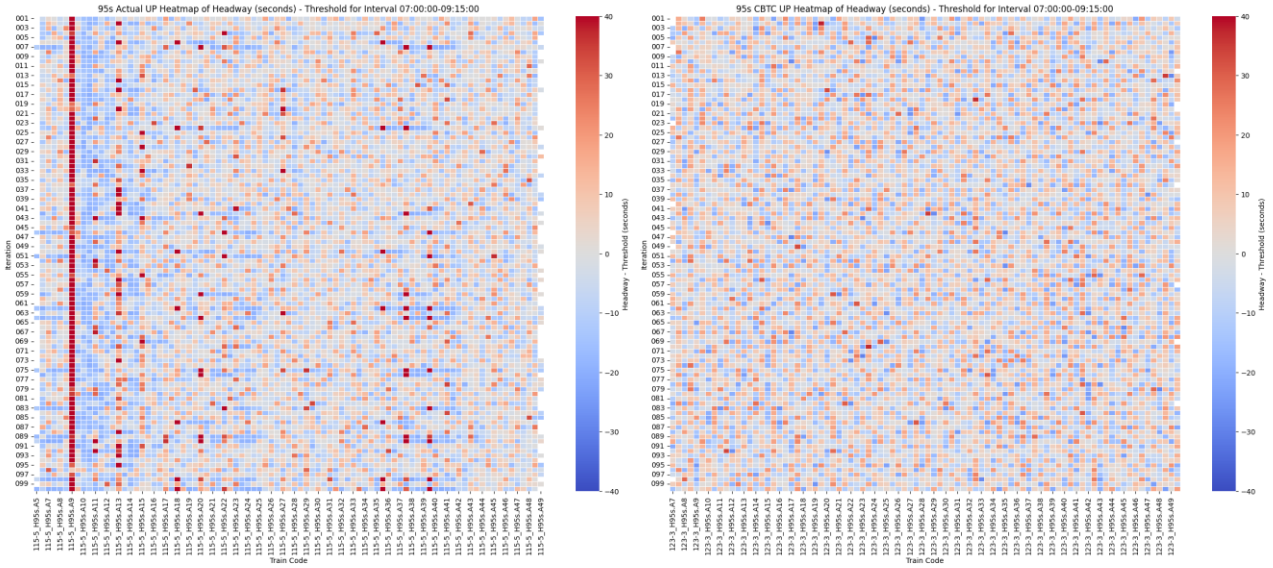

Figure 6 - Headway deviations measured at KN. Left: Legacy. Right: CBTC. Blue: realized HW shorter than planned. Red: realized HW longer than planned. White: realized HW equal planned. Lines: simulation runs. Columns: train courses.

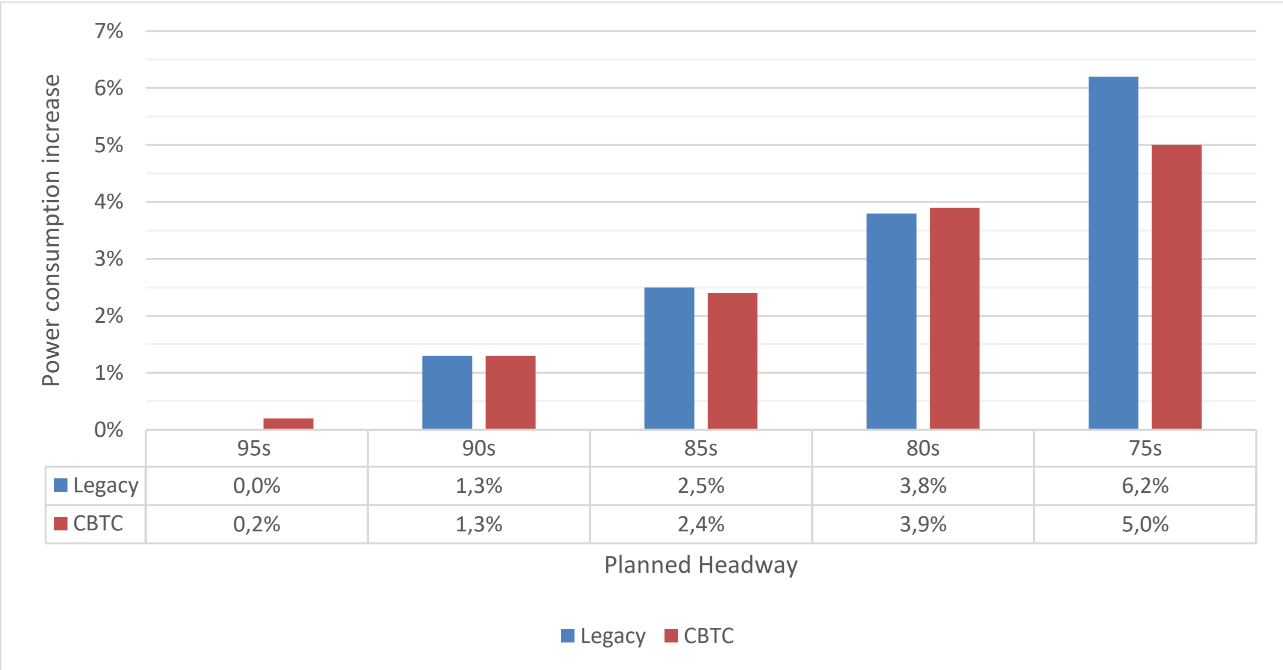

Figure 7 - Energy consumption variation as a function of the planned Headway

Energy Efficiency

The last parameter investigated in this study relates to energy efficiency. This is a preliminary study, based on assumptions and approximations, which objective is a gross evaluation of the potential improvement of a CBTC on aspects other than pure rail-traffic reliability. Only the power consumed by the individual trains was considered in this study, excluding regenerative braking and the power losses in the feeding subsystem between the electrical substations and the vehicles. The resulting power consumption values were compared to the baseline scenario, current 95 s service plan, and the comparison is reported in Figure 7. Here, a negative linear relationship is observed between headway and power consumption, as expected. The introduction of CBTC does not improve power consumption as per se. However, the system congestion in the legacy signalling for headway plans blow 80 s induces a more-than-linear relationship, due to the stop-and-go and more frequent unplanned braking and accelerations. The CBTC system reduced this congestion and its related side effects, like the increases in the power consumption, per departure. Therefore, more energy efficiency can be achieved, even though indirectly. Even though regenerative braking could reduce the energy waste by recycling part of the braking energy into the acceleration energy, it should be noticed that this technique also dissipates energy and that the energy recovery is never complete. Further studies in dedicated tools tailored for energy flow simulation might reveal the exact amount of energy regeneration for the different scenarios.

Scenario investigation: increased dwell times

The projected increasing passenger demand will stress the metro system on both the onboard and platform passenger capacity, but also on the passenger exchange at stations. The expected consequences include the extension of passenger exchange times due to larger flows, both scheduled and unexpected. This test provides the expected drop in service reliability given by such increases in the dwell times, based on the 95 s HW plan.

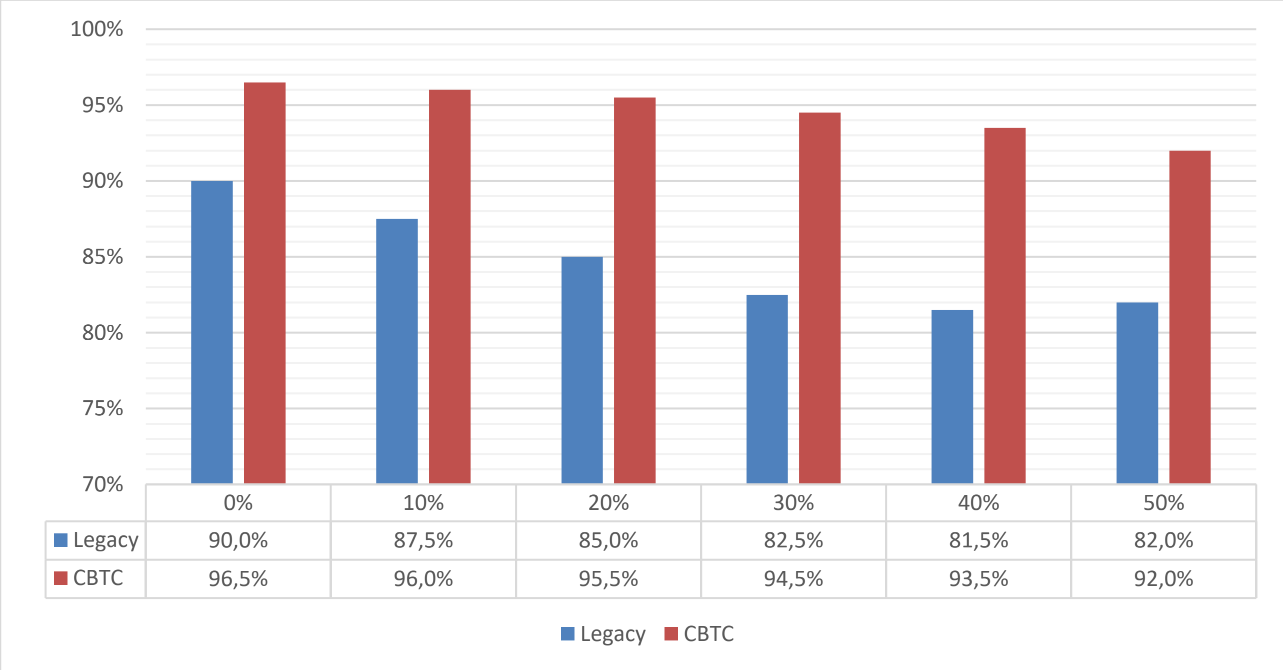

Figure 8 - SQ as a function of the dwell time extension. 95 s HW plan.

Scenario investigation: rolling stock and line speed improvement

The resignalling program in the Copenhagen Metro includes the replacement of the rolling stock as part of the renewal strategy. This gives the opportunity to identify potential operational benefits given by modifications of the dynamical requirements for the trains, possibly supported by modifications in the infrastructure that would allow higher line speed. This additional analysis is divided into a deterministic simulation to identify potential running time savings and a stochastic simulation for the improvement in service reliability.

	Travel time (s)				Relative difference from reference		
Scenario	**Reference**	**+1/6 power**	**+1/3 power**	**+1/3 power & 100 km/h**	**+1/6 power**	**+1/3 power**	**+1/3 power & 100 km/h**
VEA-VAN	1018	1006	1002	987	-1,2%	-1,6%	-3,0%
VAN-VEA	1015	1001	996	981	-1,4%	-1,9%	-3,3%
CPH-VAN	1050	1041	1032	1010	-0,9%	-1,7%	-3,8%
VAN-CPH	1053	1049	1035	1024	-0,4%	-1,7%	-2,8%

Table 3 - Running time savings by more powerful rolling stock and increased line speed.

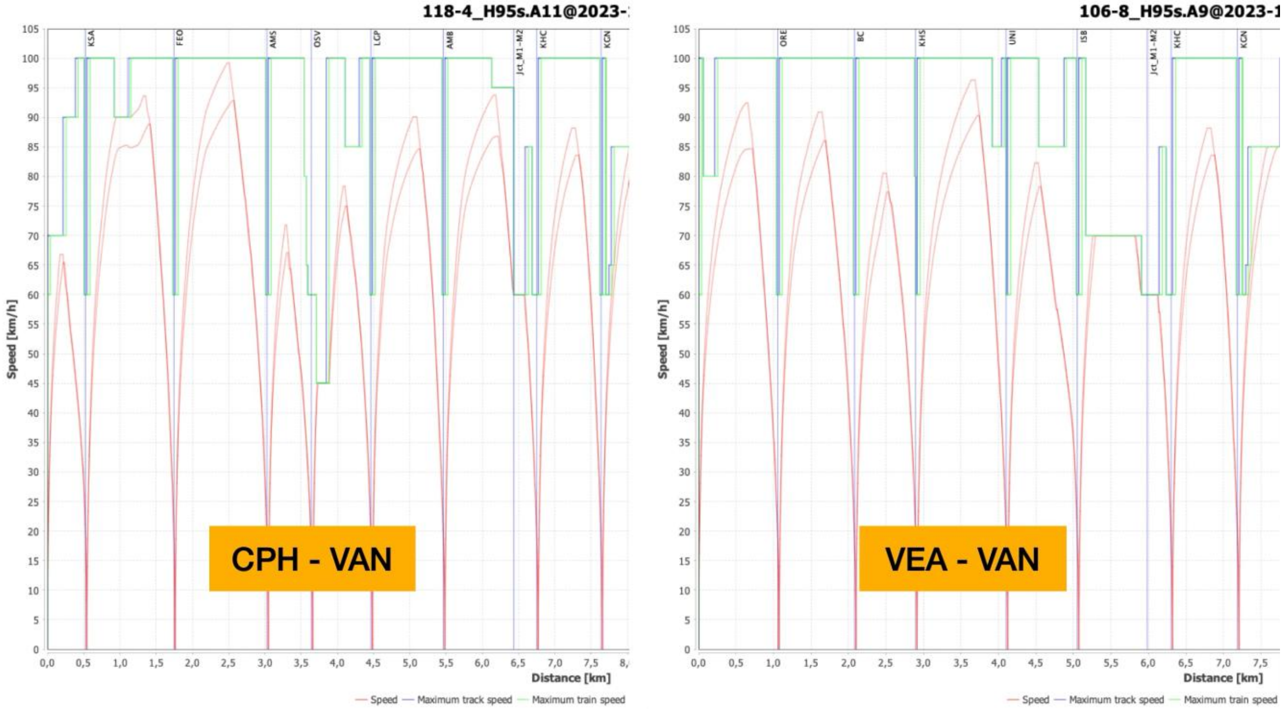

Figure 9 - Speed profiles for line speed (green) and rolling stock (current rolling stock and +1/3 power).

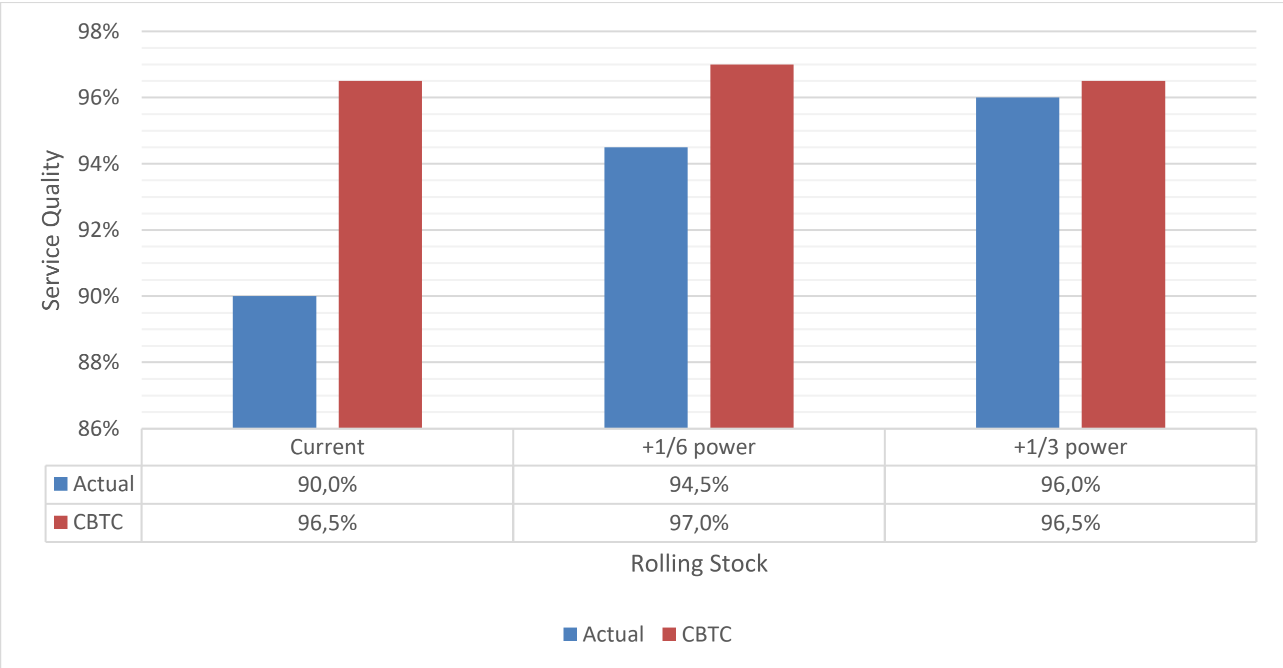

Figure 10 - Service Quality for different types of rolling stock on Legacy and CBTC infrastructure scenarios.

Table 3 shows very limited running time savings given by exclusively rolling stock power increases. This is due to the short distance between stations, which limits the potential gain by running faster or accelerating quicker. Better results are only obtained increasing the line speed in combination with the most powerful rolling stock equipment. However, the track geometry only allows for potential line speed increments in the branching sections. Furthermore, increasing the line speed is a capital-intensive operation unlikely sustainable. Figure 9 shows the line speed profile and the potential rolling stock speed profiles for the current rolling stock and the most powerful version. Speed values over the current limit of 80 km/h can only be reached in few line sections, and anyway only for brief lengths, which explain the limited running time gain.

The stochastic simulation of the current HW plan, however, highlights a substantial improvement of more powerful rolling stock in the legacy scenario. This improvement is not visible in the CBTC scenario, where SW remains at the same high level. This is likely the effect of a larger running time supplement available in the schedule when running more powerful trains. In fact, the described running time savings are on the same order of magnitude of the reduction in technical dwell time due to faster door synchronization in the CBTC scenario. The effect of such running time supplement is comparable to the dwell time supplement included in the CBTC schedule.

Overall evaluation

The radar charts in Figure 11 summarize the multi-aspect evaluation of the improvements introduced by the CBTC signalling system on M1-M2 in Copenhagen. The larger area, the better performance. Each polygon links the system scores for one given service plan (Headway). While HW and N. Trains are fixed values, independent on the signalling system, the improvement in headway stability, running time extension and energy consumption is visible for the CBTC scenario compared to the legacy system.

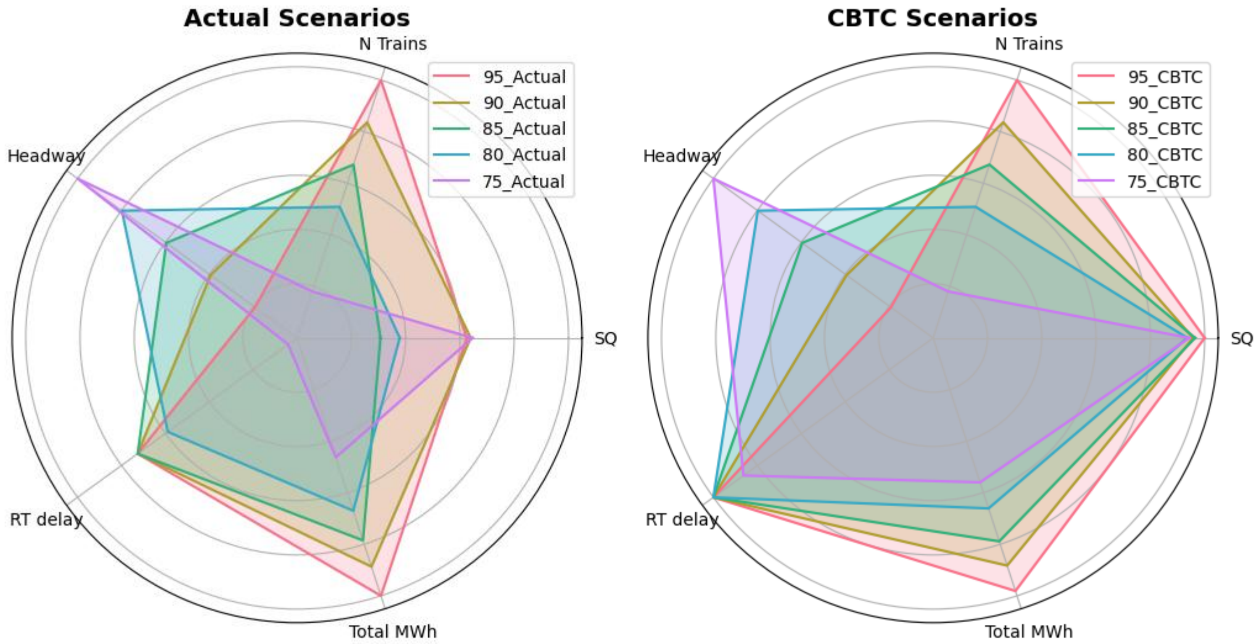

Figure 11 - Multi aspect evaluation of CBTC benefits over Current scenario. The larger value, the better score in each field.

Conclusions

This study provides a multi-aspect evaluation of the expected benefit given by the migration of a signalling system from track circuit, fixed bloc system into a moving block, CBTC. This analysis lays the basis for the definition of requirement specifications for the new signalling system to be installed on a metro system. In particular, the application on the Copenhagen Metro lines M1 and M2 shows the improvement in service reliability, both in terms of headway stability and running time reliability. In addition, a preliminary study on the energy efficiency indicates positive side effects related to the more stable operations. Not only does the reduce delay propagation provide a more stable service to the passenger, but it also ensures lower energy consumption, due to the fewer unplanned decelerations and accelerations.

The multi-aspect evaluation of the renewed system is provided in a radar chart-form, where all the improvements are collected together for a broader comparison against the reference scenario.

Interestingly, increasing the rolling stock power would expectedly gain a very limited benefit, and only in connection with the increase of line speed, due to the short distance between stations. This type of improvements is unlikely to result favourable in an overall life cycle assessment as it requires intensive investments to adapt the line speed profiles.

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