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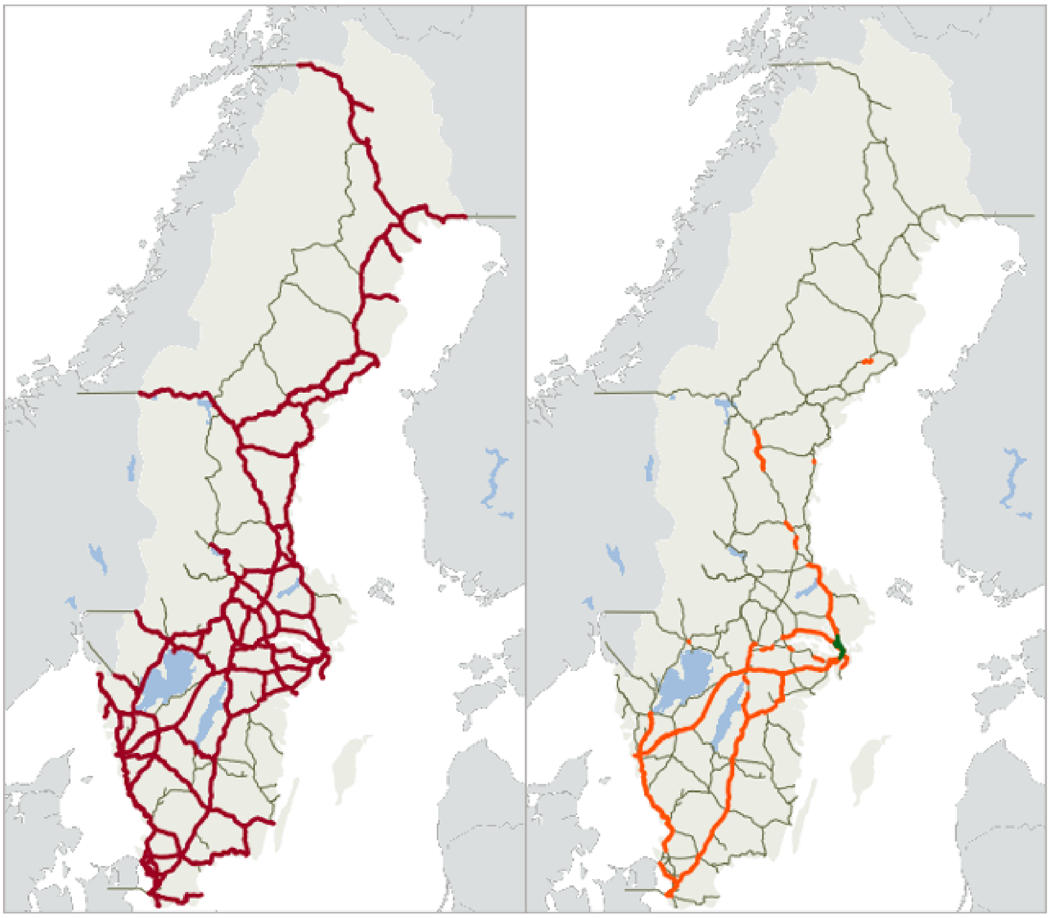

# Increasing freight transport capacity

Project report 2022:03 in the course MMS200 Project in railway technology


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PROJECT REPORT 2022:03

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MMS200 Project in Railway Technology 2022

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Cover: Railway network in Sweden. Red lines are electrified railways, orange lines are double tracks and green lines are multiple tracks. From Trafikverket [1].

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# Summary

The main objective of this report is to investigate how freight train capacity can be increased to enable transportation related to carbon capture and storage (CCS) on the Swedish railway system in order to achieve the carbon dioxide climate target.

The increased need for sustainable transport will create a large demand on the existing railway network. To meet these demands, several measures need to be taken.

To investigate this further, literature study, interviews, a case study and analysis of the current network were conducted. As the railway network is a complex system, a range of measures is suggested to counter a high capacity utilization within both shorter and longer time frames.

In the report several line segments limiting the system capacity were identified. Several measures were suggested with regards to both railway infrastructure and train set-up. It is concluded that additional investments have to be made to handle ccs transportation.

Keywords: freight transport capacity; growing freight transport demand; rail freight trains; carbon capture and storage

# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

| | |
|---|---|
| ATC | Automatic Train Control |
| CCS | Carbon capture and storage |
| $CO_2$ | Carbon dioxide |
| ERTMS | European Rail Traffic Management System |
| ETCS | European train control system |
| SEa | general reference profile in Sweden |
| SEc | reference profile for new constructions |
| SEK | Swedish krona |
| STAX | maximal axle load |
| STVM | maximal weight per meter |
| TENT-T | Trans-European railway network |

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# 1 Introduction and aim

As many other countries, Sweden expects an increase in traffic and capacity demands for the railway network in the future when the population is growing and the demands of sustainable transport is increasing. According to Trafikverket the estimated volume will increase of 64 % by cargo train and 32 % by passenger train until 2040, which will create a high demand on the railway network [2]. This project work investigates how the capacity of transports by rail can be increased and where it's required to achieve this.

By the year 2050 the United Nations, has a goal to be net-zero of carbon dioxide ($CO_2$) emissions to not exceed the global warming by 1.5 degrees [3].To achieve the climate goals of $CO_2$ emissions it is not only has to be reduced, new and innovative solutions has to be developed to process the $CO_2$ towards negative emissions. An ongoing project in European Union and the U.S is carbon capture and storage (CCS) [4]. The concept of CCS is to capture carbon dioxide from industries and to obtain capture facilities to convert it to liquid carbon dioxide. The liquid $CO_2$ is then transported by train, trucks and shipping to eventually be pumped deep down into the ground for permanent storage [5]. By the year 2045, Sweden together with other Nordic countries has a goal of reaching net-zero emissions of green house gases and by using CCS this could be possible [6]. With the help of sustainable transports such as trains, the total emissions from handling these transports on land would be minimal.
In this report, the required input data will first be discussed, including the demand for cargo transports and their origins and destinations. Furthermore, an as-is analysis is carried out, which considers, among other things, on which routes single and double tracks are available. The wagon fleet is examined in order to highlight possible improvement options. Based on this, improvement possibilities and limits will be discussed. Finally, conclusions are drawn and recommendations for further studies are provided.

The investigation can be summarized by the research questions:

- Estimate an approximated amount of yearly production of CCS and the required number of freight wagons and trains.
- Investigate possible transport corridors in order to facilitate harbors of Narvik, Trondheim, Gothenburg and Malmö.
- Identify bottlenecks that will impact these identified traffic flows.
- Identify possible solutions to capacity problems of the Swedish railway network and bottlenecks.

# 2
# Background data for the analysis

The railway network in Sweden is mainly owned and managed by Trafikverket. It extends from the far north to the south with over around 15 600 km of track where 78 percent of the track is electrified [7]. On the railway network there is an average of 530 cargo trains and 3000 passenger trains using these tracks daily, and these numbers will increase in the future [7].

The increase in both passenger and cargo trains require that the railway network is developed by building more tracks and meeting stations, and upgrading the existing railway network [7]. Figure 2.1 shows the previously mentioned electrified lines on the left and the single, double and multi-track lines on the right. As Trafikverket controls the railway network they are responsible for the maintenance of these tracks and have plans for a large expansion and modernisation of the network for the future [2].

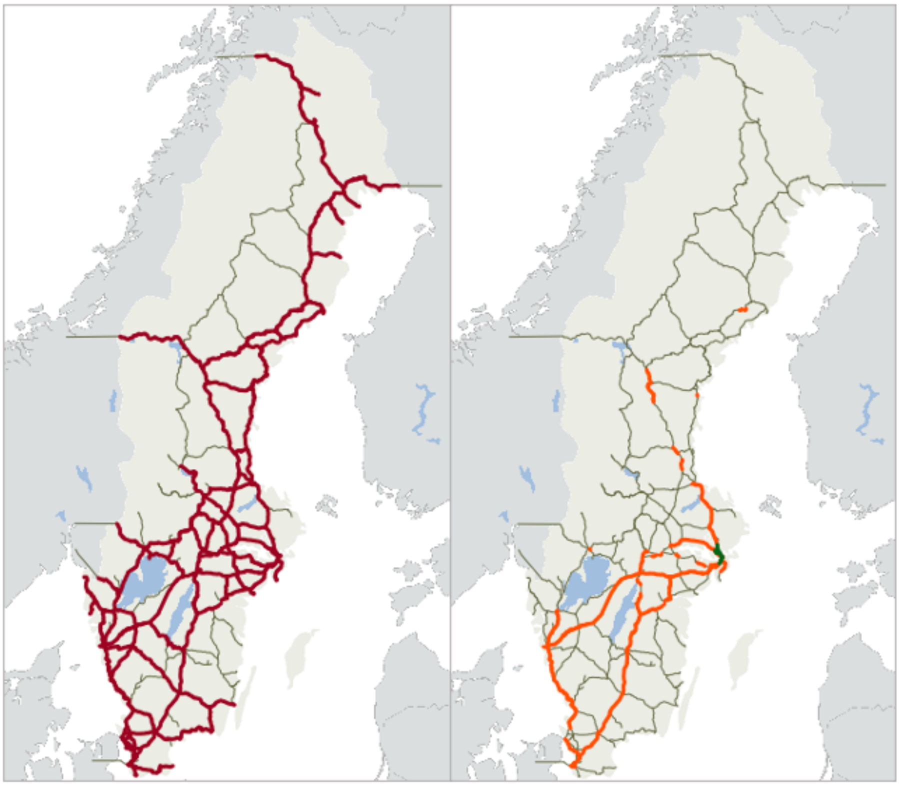


**Figure 2.1:** Map over the railway network in Sweden, to the left the electrified parts (in red), to the right the different lanes (orange: double tracks, green: multiple tracks). From Trafikverket [1].

The upgrade of the railway network is necessary both for the main tracks and the smaller tracks so that all the parts of the network can be accessed and utilised. The expansion includes both to build new tracks and upgrade the single lanes and double lanes [2]. Although the upgrade of tracks is necessary, the upgrade is not only very time consuming and expensive, but also might prevent the tracks for being used for periods. However, the railway network is not the only area that needs an upgrade, the modernization of signal systems and digitalisation is also essential for the future.

## 2.1 Liquid carbon dioxide

Globally, humans will in the future continue to produce $CO_2$ in many different ways. Renewable energy such as wind, water and sun is a good way for reducing the green house gas emissions but additional processes are needed to reduce it even further [8]. Carbon capture and storage, also known as CCS, is a fairly new technology that has the potential of capturing large amounts of $CO_2$ from the atmosphere and from different industries by converting the gas to liquid [8].
The liquid $CO_2$ is then transported by train, trucks or pipes to harbours where it is loaded on large ships. These ships transport the liquefied $CO_2$ to facilities where it is pumped into cavities deep into the ground where it is stored [8]. The transportation and storing of liquid $CO_2$ has certain requirements. For the liquefied $CO_2$ to stay in

its form it needs to be pressurized by 8 bar and have a temperature of -40 degrees celsius. This creates certain demands on the train carts, the transportation time and storage [9].

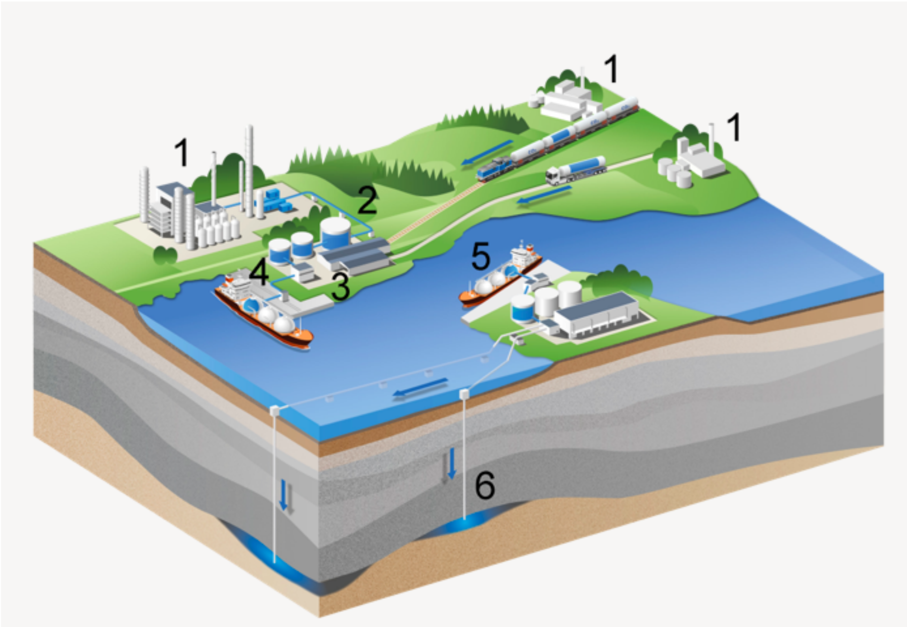



**Figure 2.2:** Process of CCS from industries to storage. From Port of Gothenburg [5]

The processes in the figure above are:

1. Capture of carbon dioxide gas at facilities from the atmosphere and large industries that produce $CO_2$.
2. Transportation of liquid $CO_2$ to the harbour by train, trucks or pipelines.
3. The liquid $CO_2$ is stored temporarily in the harbour.
4. The liquid $CO_2$ is loaded onto ships.
5. The ships transport the liquid $CO_2$ to facilities off-shore.
6. The liquid $CO_2$ is pumped deep into the ground.

Since the industries where $CO_2$ is captured are spread out all over the country, it needs to be transported to the harbours in the most sustainable way [10]. In Gothenburg, a project named CifraCap (Carbon Infrastructure Capture) has been initiated by a group of large industry companies (Göteborgs Energi, Nordion Energi, Preem, St1, Renova and Göteborgs Hamn AB) [6]. The goal of CinfraCap is to find an optimal infrastructure solution to transport the $CO_2$ in a sustainable way with the lowest emissions [6]. One of the most suitable ways to transport this kind of cargo when looking on the emissions (per ton-km) and transportation times is by train [11].

## 2.2 Analysis of railway network

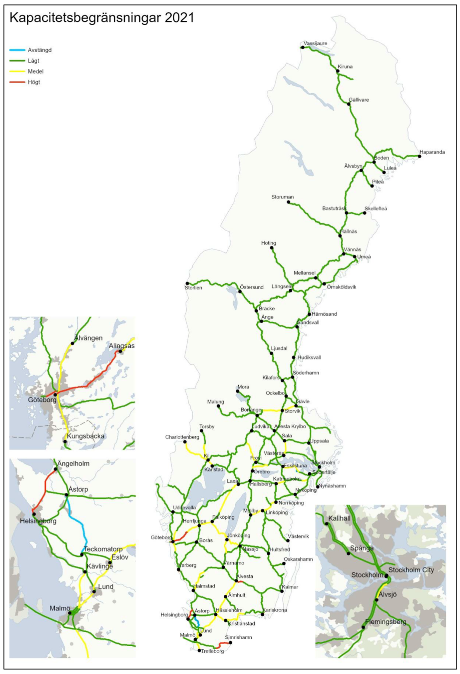
When preparing for an increase in capacity of the railway network and the potential transport increase of liquid $CO_2$ in the future, numerous of different input data that need to be analyzed. This input data will be based on current data and estimations about the future.

### 2.2.1 Current railway network situation

The Swedish railway network consists of single track-, double track- and multiple track systems. In 2020, the Swedish railway system consisted by 10,909 km of lines and of this length only 2,056 km was double or multiple tracked lines [12]. Trains are limited in length by lengths of meeting stations and platforms. The current system is adapted for trains with maximum length of 630 meters with some exceptions on a few stretches that allow trains up to 750 meters.

The traffic control system is also affecting the possible length of trains [13]. In 2010 the first line in Sweden was equipped with the new traffic control system European Rail Traffic Management System (ERTMS) and it was expanded to 573 kilometers by 2020 [12]. The remaining railway lines are controlled by either Automatic block system and centralised traffic control system (7,546 kilometers) and "Automatic Train Control" (8,069 kilometer) ATC for short [12]. Network characteristics mentioned above are some of the factors that are affecting the capacity of the railway system. In figure 2.3(b) it's shown that on a daily average there is generally a low limitation of capacity on the Swedish railway system, but with some line segments that are heavily limited thus creating bottle necks in the system. The situation during the two hours with the maximum limitation are shown in figure 2.3(a). It is seen that for these specific time frames, the limitations over the whole system are much higher. The 2 hour peak have 22.5 % of the line in the red zone compared to the daily average which has 2.4 % in 2021 [14].


((a)) Max 2 hours period




((b)) Daily average

**Figure 2.3:** Capacity limitations in the Swedish railway system. From [14] Green = low capacity utilization (≤ 60 %), Yellow = medium capacity utilization (61-80 %), Red = high capacity utilization (81-100 %).

### 2.2.2 On-going development projects

Trafikverket has long going plans for new projects that are set out to remedy and improve the railway system according to identified criteria and analysis, all presented in the implementation plan [2]. There are until year 2025 47 projects planned to improve freight transportation, and 22 projects aimed to improve the general capacity on the railway system [2].

As part of the trans-European railway network (TENT-T), by 2035 all of lines in Sweden are planned to be equipped with ERTMS [2]. Connected to the TENT-T, lines shown in figure 2.4 are recognized as important routes for freight transports that will be prioritized to handle operations by trains with length of 740 meters [13]. New meeting stations are by default built to handle trains of 750 meters [15].


**Figure 2.4:** Main network focused to handle an increased train length. From [13]

## 2.3 Train capacity evaluations

When looking at train setup, weight, width, length, speed and type of locomotive are important parameters for increasing capacity of freight transport.

The weight of a freight train is limited by the load carrying capacity of the railway. There are two important parameters when looking at the load carrying capacity, maximal axle load (STAX) and the maximal weight per meter (STVM). STAX and STVM are both used to specify which structural capacity bridges and embankments should withstand. In Sweden the general STAX is 22,5 tonnes and STVM is 6,4 tonnes. However, many stretches allow heavier freight trains with STAX 25 tonnes and STVM 8 tonnes. Malmbanan even allow STAX 32,5 tonnes and STVM 13 tonnes. For new constructions, the minimum STAX should be at least 25 tonnes and STVM should be 8 tonnes. This will allow cargo trains to load heavier and thereby increase their freight capacity [13].

Wider train wagons enable more loading volume. When looking at width and height of wagons, reference profiles are relevant. Reference profiles are the width and height that trains can have without risking contact with other trains or constructions. The general reference profile in Sweden is SEa, with a width of 3,4 meter. SEc is the reference profile implemented for new constructions, it has a width of 3,6 meters. SEc would enable more cargo volume in each wagon and thereby increase freight capacity [16].

The typical maximal speed for freight trains in Sweden is 100 km/h. Although, many freight trains are allowed to run at faster speeds [16]. When loading heavier, trains drive slower due to regulations and the fact that acceleration and deceleration take longer time. Slower trains affect the capacity of railway since it can lead to disturbance of other trains. To compensate for the extra weight, the trains need stronger locomotives with effective braking systems and running gear. Often, multiple locomotives are used for one freight train. Up to three locomotives are used in Sweden for freight trains [15].

According to Green Cargo there are three locomotive types that are relevant for $CO_2$ freight operations in Sweden, these are Rc, Re and Mb locomotives [9]. The wagons that will be used for transporting liquefied carbon dioxide are Zacns wagons. The specifics for these locomotives and wagons are shown in table 2.1 and 2.2. Through locomotive length, hauling capacity, and length, weight and max cargo weight of wagons, the max length, max cargo weight and max number of wagons can be calculated for different train setups, see table 2.3. The max cargo weight was calculated through multiplying the number of wagons of each train set-up with the max cargo weight of one wagon. Although, these values are for optimal conditions, factors such as which braking system is used have an effect on the capacity.

**Table 2.1:** Specifics for Rc, Re and Mb. Values from [9]

| Loco type | Rc | Re | Mb |
|---|---|---|---|
| Weight [tonnes] | 78 | 84 | 123 |
| Length [m] | 16 | 18,9 | 20,7 |
| Max speed [km/h] | 135 | 140 | 160 |
| Capacity [tonnes] | 1600 | 1800 | 3 000 |

**Table 2.2:** Specifics for Zacns wagons. Values from[9]

| Wagon type | Zacns |
|---|---|
| Weight [tonnes] | 28 |
| Axle load [tonnes] | 22,5 |
| Cargo weight [tonnes] | 62 |
| Length [m] | 15 |

**Table 2.3:** Number of wagons, max length and cargo weight of freight trains depending on locomotive type and number of locomotives.

| Loco type | specification | 1 Loco | 2 Loco | 3 Loco |
|---|---|---|---|---|
| Rc | number of wagons | 17 | 35 | 53 |
| Rc | max length [m] | 271 | 557 | 843 |
| Rc | max cargo weight [tonnes] | 1054 | 2170 | 3286 |
| Re | number of wagons | 20 | 40 | 60 |
| Re | max length [m] | 318,9 | 637,8 | 956,7 |
| Re | max cargo weight [tonnes] | 1240 | 2480 | 3720 |
| Mb | number of wagons | 33 | 66 | 100 |
| Mb | max length [m] | 515,7 | 1031,4 | 1562,1 |
| Mb | max cargo weight [tonnes] | 2046 | 4092 | 6200 |

## 2.4 Increased need of transportation capacity

This chapter discusses origin and possible destinations of cargo transports. This is discussed on the basis of the Zeroc project [10] and other sources.

### 2.4.1 Origin and quantification of carbon dioxide transport

To evaluate where the origin of the freight transports are, the Zeroc project has elaborated where the largest $CO_2$ production sites are [10]. The three largest districts are:

- Västra Götaland
- Norrbotten
- Gotland

This data will be used as a basis to determine where the source of captured carbon dioxide is. As the railway network does not cover all areas of Sweden, the origin of freight transports must later be investigated in more detail. Furthermore, they must also be quantified according to place of origin. Figure 2.5 shows sites with emissions of between 100 kton/year and 500 kton/year and more than 500 kton/year. It is noticed that the places of origin are on the east coast and in the southern part of Sweden.

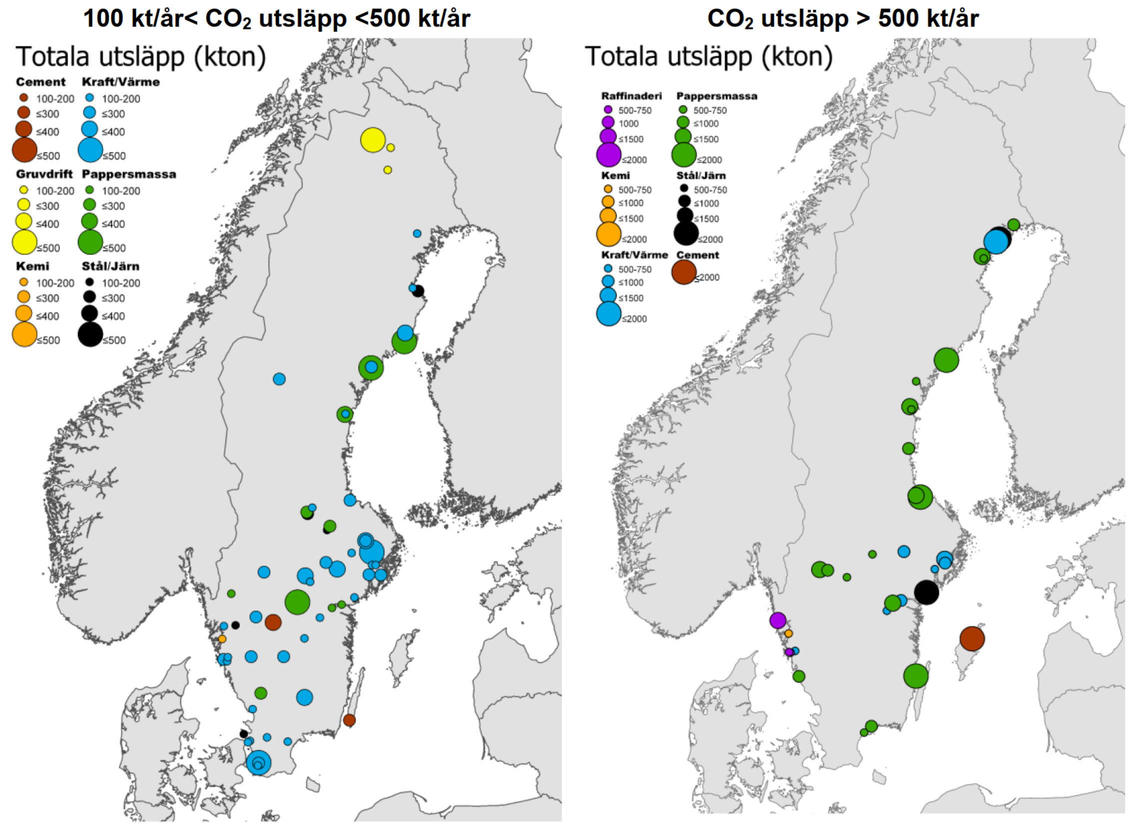



**Figure 2.5:** Fossil and biogenic sources with combined emissions of $\geq$ 100 ktons $CO_2$. From Zeroc project [10]

As a first step, the origins that have an emission greater than 500 kt/year are examined. This is chosen because transports from these origins can be handled in a more bundled fashion. In Figure 2.6 the railway network and places of origin of the transports have been overlaid. It is noticed that the places of origin and the railway connection are very close to each other.

This shows that transport by rail can be an option. If a company does not have a rail connection, intermodal transport may be possible. This will be examined in more detail in the following chapters. A more detailed investigation of whether a company has a rail connection will make sense in the future if a precise time schedule is known for when it is possible for a company to capture $CO_2$.

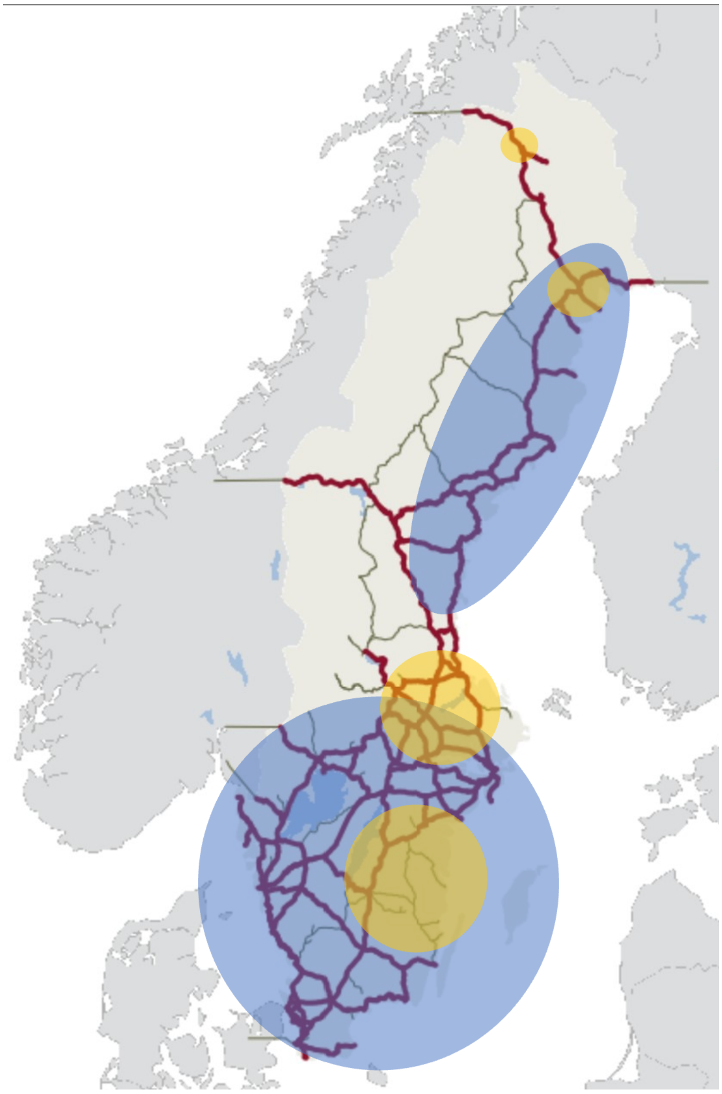


**Figure 2.6:** Railway map of Sweden with hotspots (blue) and individual producers (yellow) of $CO_2$ emissions. Background map taken from Trafikverket [1].

### 2.4.2 Destinations of carbon dioxide transports

To identify bottlenecks in the current system it is essential to know where the transports are going. As described in chapter 1, the focus of the project is on liquid carbon dioxide transportation to the sea. The Zeroc project [10] has planned a shipping route along the west coast, which includes the following stops:

- Malmö (railway connection, new infrastructure needed),
- Höganäs (no railway connection),
- Södra Cell Värö (factory close to the harbour),
- Gothenburg (electrified, new infrastructure planned),
- Stenungsund (harbour area has to be electrified),
- Preem Lysekil (refinery next to the harbour).

As relevant for this study, the ports of Malmö and Gothenburg on the west coast of Sweden are identified as destinations. Since the final depository of the captured $CO_2$ are in burrows under oil platforms located in the North Sea, the following ports on the West Coast of Norway also come into question:

- Oslo
- Bergen
- Trondheim
- Narvik

Due to the distance to Sweden the harbour of Bergen is not expected to influence rail transportations in Sweden. Furthermore, it is to be expected that Oslo will handle the carbon dioxide from Norway. Therefore it is expected that the harbours in Narvik and Trondheim will handle transports from the northern part of Sweden. The railway network of Sweden is supporting these harbours, since there are direct connections between Luleå - Narvik, and Sundsvall - Trondheim. The link between Åre and Trondheim is going to be electrified in the year 2024 [17]. Then all of this links are electrified except for the unloading and shunting yards at the harbours. The loading yards at the companies were not investigated because at this stage it is not yet known which companies will implement the system first.
In the future, more facilities can be used on the sea in the east of Sweden or the eastern ports can be used for transport. Therefore the largest harbours on the east coast with railway connection are listed. According to [18] these are:

- Luleå
- Stockholm
- Gävle
- Karlshamn
- Oxelösund

As the focus of this project is on the Zeroc project and it is not assumed that the eastern ports will be needed in the first implementation step, they will be neglected in the following. In summary, the following ports are considered to be relevant for the handling of transports by rail at this stage: Malmö, Gothenburg, Trondheim and Narvik.

# 3

# Analysis and results

In this chapter, possible bottlenecks and possibilities for improvement are worked out. This has been divided into an infrastructure part and a train setup part. The infrastructure part deals with the capacity analysis of the schedule, single-track and double-track lines. The train setup part deals with strengths, weaknesses and improvement possibilities of the locomotive or train composition. Finally, a numerical case study is given for a concrete link.

## 3.1 Identification of bottlenecks

In chapter 2.2 limitations in the Swedish railway network are presented, with this data, together with origins and destinations of the carbon capture cargo transports in chapter 2.4, this chapter will identify segments of lines that will be limitations for extended freight transportations.

### 3.1.1 Traffic flow identification

Green Cargo has determined traffic flows according to figure 3.1 [9]. These are largely consistent with the origins and destinations from chapter 2.4. Flows are to be listed here:

- Luleå - Narvik
- Sundsvall - Trondheim
- Gävle (Fredriksskans) - Göteborg (Oslo)
- Norrköping - Malmö

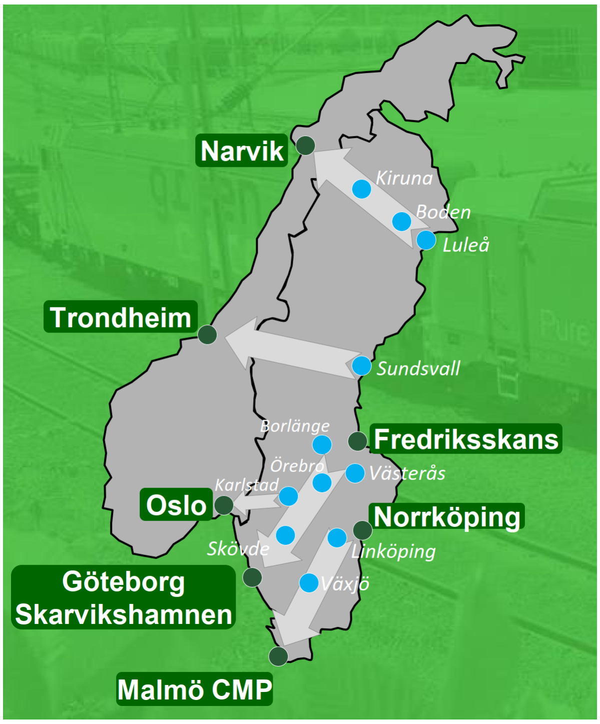



**Figure 3.1:** Traffic flows identified by Green Cargo. From [9]

### 3.1.2 Segments of limited capacity

Comparing figure 2.3(b) with traffic flow in figure 3.1, a number of segments with a capacity utilization over 61 % on a daily average, can be highlighted as potential problems for an extended freight transportation. These segments are:

- Laxå - Göteborg
- Flen - Katrineholm
- Norrköping - Mjölby
- Alvesta - Malmö

The segment Laxå - Göteborg contains a line segment, Alingsås - Göteborg, with a utilization level of 98 % which is second highest in the country. The remaining segments in the list are between 61-80 % [14]. Segments with a capacity utilization like these have according to Kapacitetscenter [14], a surplus of capacity (except Alingsås - Göteborg). The level might however cause a problematic maintenance situation with too few available time slots for maintenance work and also to provide desired traffic flow from the operators. Segments exceeding 81 % are prone to even higher disturbance [14].

In table 3.1 the highest allowed speed for the different stretches is presented.

The line segment Flen - Katrineholm is the only segment that does not have meeting stations with capacity for 730 meter trains [1]. All four segments are equipped with the ATC signalling system [1].

**Table 3.1:** Highest allowed speed for different locomotives and wagon with STAX 22.5 From [19]. (Where the x indicates that the locomotive can be driven at highest allowed speed for stretch/type of vehicle)

| Line segments | Rc | Re | Wagon with stax 22.5 |
|---|---|---|---|
| Laxå- Göteborg | x | x | 100 |
| Flen - Katrineholm | x | x | 100 |
| Norrköping - Mjölby | x | x | 100 |
| Alvesta-Malmö | x | x | 100 |

## 3.2 Increased capacity by utilization of infrastructure

In this chapter we discuss how to increase capacity on the infrastructure. First this is done on the basis of the timetables, then on the basis of the distinction between single and double track.

According to Trafikverket [1], the following stretches are mainly double track:

- Fredriksskans - Göteborg
- Norrköping - Malmö

According to Trafikverket [1] following links are mainly single track, which is important for our project:

- Luleå - Narvik
- Sundvall - Trondheim
- Luleå - Sundsvall
- Sundsvall - Gävle

As mentioned in chapter 2.2.2, there are multiple construction projects on-going or planned. The following projects are highlighted as they are relevant for freight traffic:

- Hallsberg-Malmö. Double tracks between Hallsberg and Degerön. To be finished in 2030. [20]
- Hässelholm-Lund. Double tracks. To be finished in 2029 [21].
- Umeå-Luleå. Double tracks. To be finished in 2030 [22].
- Malmö-Lund. Four tracks. To be finished in 2023 [23].
- East-Link. New double-track railway between Järna and Linköping. To be finished in 2035 [24].

The increase in capacity for single and double tracks are discussed in the following sub-chapters.

### 3.2.1 Increasing capacity by scheduling

When looking at the time schedule of the railway network there are two peaks where the capacity is significantly higher that during the remaining hours. The peak hours around larger cities are during the morning rush between around 06.00-09.00 and in the afternoon 15.00-18.00 [25].

One way to increase the capacity is to utilize the gaps between peak hours. Filling the gaps by running more cargo trains during the night would utilize existing capacity, but would give less time for maintenance work and other usage of the railway. Since the tracks are in great need of being maintained, preferably during low traffic times, it would put more tension on the tracks and would lead to greater costs in repairs and restricted usage of the network [14]. Also if a train would start at one place in night to fill the gaps, it could interfere with trains around larger cities when the morning peak hour occur and the capacity utilization of the tracks is high.

There are other ways to optimize the time schedule. One possible way is to have all the trains travel at the same speed. When there is a mix of high speed trains and low speed trains the capacity is lowered and the time that trains stay on the tracks is increased [26].Another possible way to optimize the time schedule is to have larger blocks of trains going in the same speed in one way without oncoming traffic. But because of the time table of passenger trains is strictly managed it would be hard to implement [26].

### 3.2.2 Increasing capacity for single tracks by infrastructure development

In addition to the scheduling, distances between meeting stations are important for the capacity. It is important to have a similar distance between meeting stations to maintain high and fluent traffic flow. If this is not the case, not all meeting stations can be fully used, as stations with short distances can only be used as much as stations with wide distances [27]. Figure 3.2 shows the meeting stations on the single track sections on some lines. It can be seen that they are approximately equally distributed. It is assumed that the respective meeting stations are approximately 750 m long. If the additional cargo transports cannot be compensated by the maximum utilisation of the schedule, the first recommendation is to set up more meeting stations. This means that more trains can run on one link. The homogenisation depends on the longest link between two meeting stations. If this is not possible for space reasons, another possibility is to extend the meeting stations to 1500 m so that two trains can wait for oncoming traffic. As a result, more trains can run in close sequence at a homogeneous speed to the next meeting station, which leads to an increase in capacity. If longer freight trains are possible, they can be handled on lines with longer meeting stations. According to Atanassov and Dick [28], only half of the meeting stations need to be lengthened to maintain a high quality of service in mixed traffic (long and short trains). If more than 50% of the meeting stations are extended, delays in the system can be compensated and traffic bundling can take place, according to Atanassov and Dick [28].

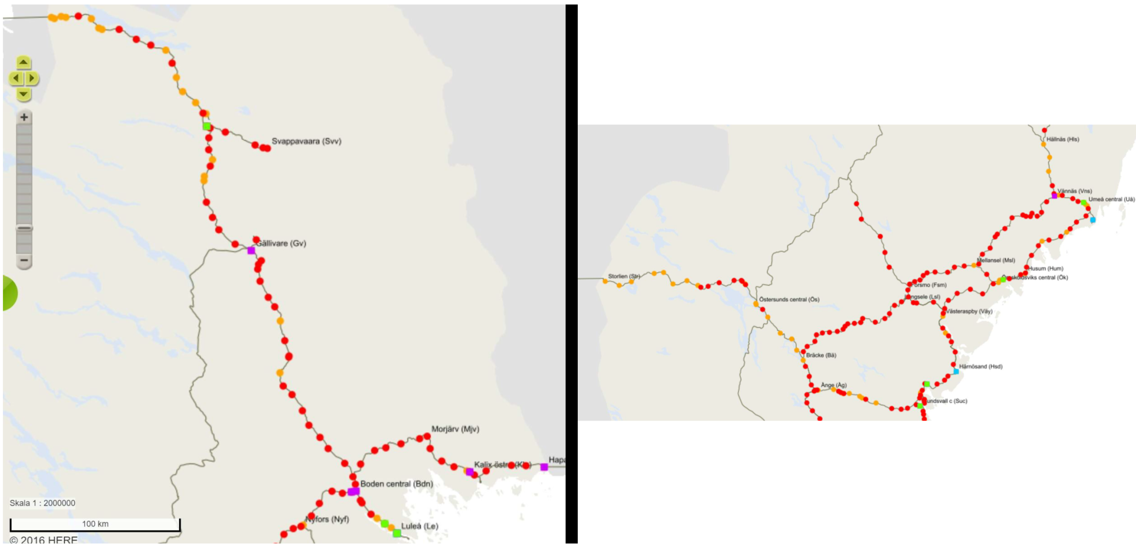



**Figure 3.2:** Railway map between Luleå - Swedish border towards Narvik and Sundsvall - Swedish border towards Trondheim. From Trafikverket [1]. Orange dots are operational points with passenger exchange, red dots are operational points with no passenger exchange, purple quadrangles indicate loading areas for freight, green quadrangles indicate railway connection to intermodal terminals.

A high capacity on the rail is generated by a high homogeneity, for example by equal speeds, and equal priority [29]. Variation in speed depends on the maximum speed of a train and the speed limit of the track. Since bottlenecks form at points with maximum capacity utilization, sufficient waiting space must be provided at the transitions in order to work through the bottleneck in low-traffic times, otherwise the bottleneck will spread into the system. Such a transition can be found in the area between Abisko and Narvik, see figure 3.3. There are speed variations that affect freight traffic, especially in the area around Narvik, where there is a speed limit of 40 km/h. This can be compensated by parking and unloading areas. The area around the border and especially towards the Norwegian inland is more critical, as there is not so much space to park the trains and to guarantee the flow of traffic to the port. For the link between Åre and Trondheim such a bottleneck is not existing, see figure 3.4.

In summary, it can be said that the number of meeting stations, their length and the spacing are limiting factors for single-track lines. If the capacity limit is reached and cannot be compensated for by the schedule, it is recommended to build more or longer meeting stations. This leads to more trains being able to use the link and, in the case of a lengthening, to a bundling of trains. Furthermore, an extension of the meeting stations ensures that longer trains can run there in the future.

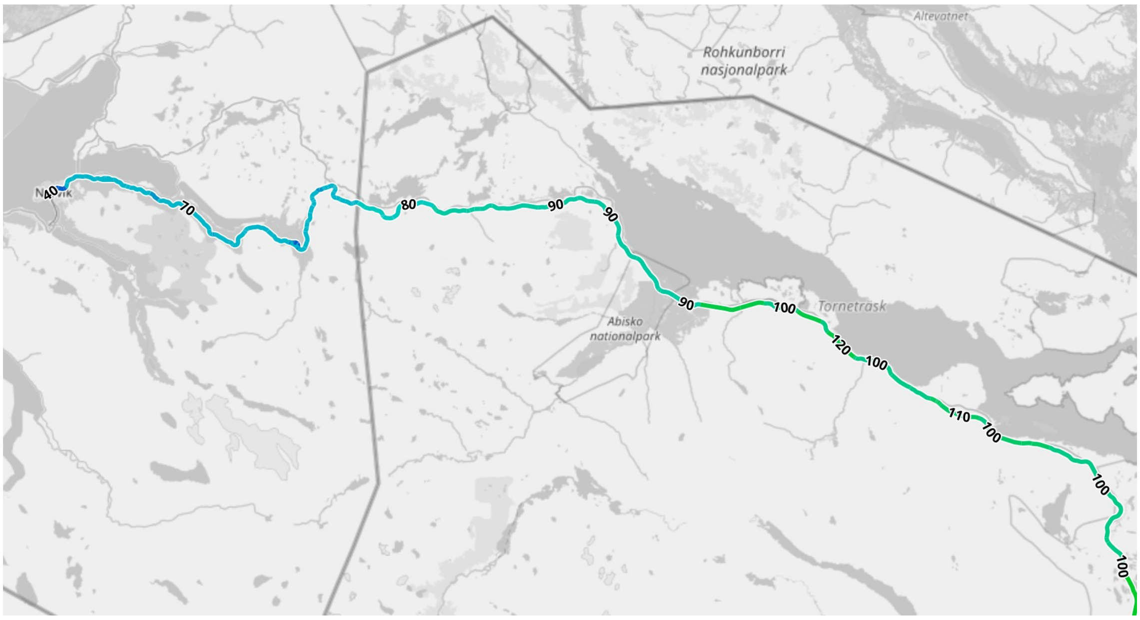



**Figure 3.3:** Speed restrictions between Abisko and Narvik. From OpenRailwayMap [30].

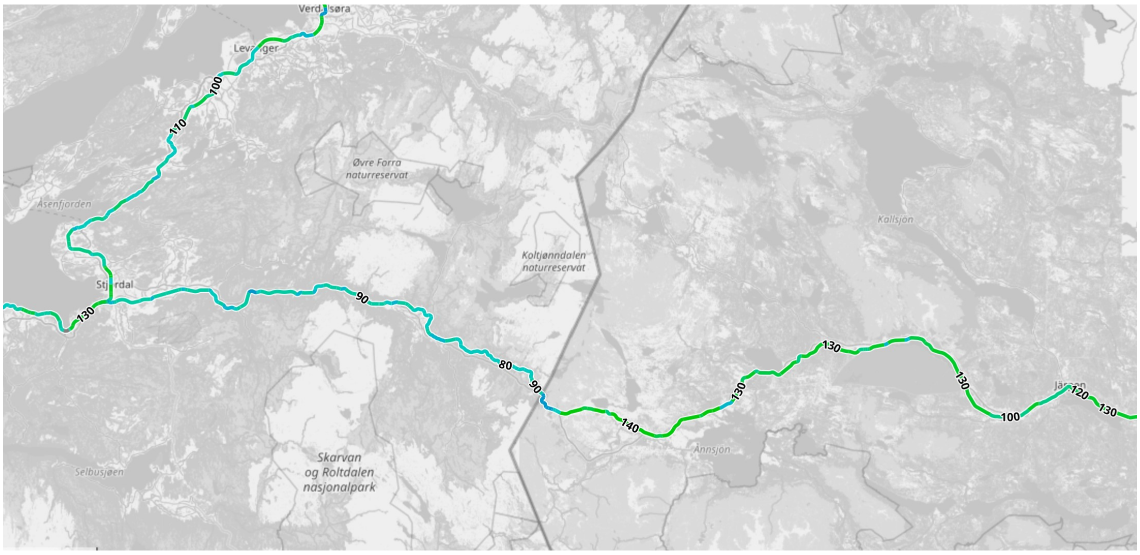



**Figure 3.4:** Speed restrictions between Trondheim and Åre taken from OpenRailwayMap [30]

### 3.2.3 Increasing capacity for double tracks by infrastructure development

In addition to the investigation of single track lines in the previous chapter, double track lines must also be analysed. According to Figure 2.1, these are currently mostly to be found between central and southern Sweden. A double track line is characterised above all by the fact that directional train traffic can be carried out separately. In order to achieve an increase in capacity, either the signalling system or the operating procedure can be changed [31]. The signalling system, as described in chapter 2.2, currently runs on the ATC or European train control system (ETCS) system. An ETCS system can operate on 3 levels. Sweden has set the goal to establish ETCS level 2, which operates without signals and displays the respective driving commands on the instruments [32]. Another possibility to increase capacity is to shorten the block sections, as these have a higher relevance for slower traffic than for fast rail traffic [33]. This would require more insulated joints and be more costly. Separating passenger and cargo traffic leads to higher capacity [33].

Another possibility is to homogenise speeds, but this would significantly increase travel times for passenger trains. According to Abril et al. [33] on double tracks the influence of the train heterogeneity is higher than the influence of train speed heterogeneity. A combination of operational and constructional improvements, according to the Network of European Railways [31], the construction of new switches that can be used at high speed would allow overtaking for fast trains on the open track. This can be thought of as an overtaking procedure on a country road. The overtaken trains would only have to reduce their speed minimally and in the best case the procedure can be completed without stopping. This requires that on of the tracks are less frequently trafficked, as the procedure demands free time slot on the passing track.

## 3.3 Increased capacity by train set-up

To increase capacity by train set up the freight trains need to get longer, heavier, larger or faster.
It is a complex task to increase the length of freight trains in Sweden. For longer trains than 630 meters, railway infrastructure needs to be improved. Meeting stations, passing loops and railway yards need to be able to handle trains longer than 630 meters. This requires rebuilding of the current railway network. According to Froidh [16] the estimated cost for increasing all meeting stations, passing loops and train yards to 1000 meters for all freight corridors is 21 billion SEK. This would increase the general freight capacity by 50 %. But this requires that there is available space next to the meeting stations and train yards. Another improvement that needs to be done is new braking percentage tables for the railway. Braking percentage tables decide the maximal speed for trains depending on the braking capacity of trains. The present tables were done in 1980 and only allow trains up to 730 meters. This measure will not be expensive to implement [13].

Heavier trains on the current network require rebuilding. It will be very expensive to increase the maximun allowed axle load (STAX) and weight per meter (STVM) on the network since it requires new construction or rebuilding of the current system. To increase the carrying load through rebuilding is an extensive and expensive process. Therefore, it might be more beneficial to increase the carrying capacity when constructing new railway sections. Much of the railway network in Europe is restricted to STAX 25 tonnes which prevents heavier international freight transportation [13].

For more loading capacity on the trains, the wagons need to get larger. Therefore, the railway infrastructure needs to be able to manage with wider reference profile as SEc. This will not be expensive since the railway has been built to manage larger reference profiles. This would result in more cargo being transported in each wagon and thereby increase capacity [13].

To increase speed on freight trains there are many improvements that have to be done. As earlier mentioned, new braking percentage tables are needed to allow longer trains. Another factor that need to be considered is the noise and vibrations from freight trains. Increased speed leads to increased noise and vibration. The increased noise can be reduced through noise barriers and the vibration can be reduced through soil stabilization. The locomotives and the running gear is an important element when looking at speed of freight trains, they need to be able to operate in high speeds. Another important aspect is that the brake capacity also needs to be increased to allow for faster trains. This can be done through usage of more efficient brakes. Freight trains with maximal speed of 120 km/h requires SS-brakes and a maximal speed of 160 km/h requires SS-brakes and EP brakes along with braking rules. These measures require investments from both the operating companies and the Swedish government [16].

## 3.4 Case study based on possible links

In this chapter three example studies are showing how many trains that would be needed for the links Luleå – Narvik, Gävle – Gothenburg and Norrköping – Malmö. It is first assumed that the larger companies with the most $CO_2$ emissions have the possibility to convert the emissions into liquefied $CO_2$. The places of origin according to Figure 2.6 were taken with the values from the Zeroc project [10]. The values were assumed to be maximum in each case and presented in table 3.2.

**Table 3.2:** Origin of the $CO_2$ transports and amount. Data taken from the Zeroc project [10].

| Origins | Emission [ktons/year] |
|---|---|
| Luleå (steel & heating industry) | 4000 |
| Kiruna (mining industry) | 500 |
| Gävle and Stockholm area | 7500 |
| Norrköping and southern Sweden | 8500 |

In order to determine how many train sets that are needed to transport the $CO_2$, the following formula 3.1 was created. At this point in time, it is not yet predictable when $CO_2$ transports will be the case and what storage options will be available at the production sites or destinations. The formula determines the number of additional $CO_2$ trains on a daily average over the year. The maximum load per train is taken from Chapter 2.3 and the emission quantity from Table 3.2.

$$\#_{\text{trains}} = \frac{emission_{\text{perOrigin}}}{haul_{\text{perTrain}} * 365} \tag{3.1}$$

The calculated values are shown in Table 3.3, the exact numbers in Table 3.4. It can be seen that there is a very large amount of cargo to be transported, depending on the train, and it should be noted that this number applies in one direction only. In order to put these numbers into perspective, the current forecast of freight train path usage is looked at. In figure 3.5, for example, the traffic volume between Alingsås-Göteborg is between 64-65 trains a day. This is the same route that may get used for the Gävle and Stockholm area resulting in increase of 12 %. If this is compared with the new number to be implied per day, the bottlenecks cannot handle this traffic. It should be noted that the wagons are empty on the return journey if they cannot be used elsewhere. Therefore, more wagons can be attached to a locomotive due to not being loaded. It can be concluded that fewer trains occupy the infrastructure for the return journey. A more detailed examination of the respective links should take place when it is known which companies can implement this new system first and whether they have a rail connection, or whether a multimodal transport is possible.

**Table 3.3:** Additional amount of train units needed for one direction

| | **Number of train units needed in one direction** | | | |
|---|---|---|---|---|
| **Origin** | **2 Re locos** | **1 Re loco** | **1 Rc loco** | **1 Mb loco** |
| Luleå | 4,42 | 8,83 | 10,44 | 5,35 |
| Kiruna | 0,55 | 1,10 | 1,30 | 0,67 |
| Gävle and Stockholm area | 8,28 | 16,57 | 19,56 | 10,02 |
| Norrköping and southern Sweden | 9,39 | 18,78 | 22,17 | 11,35 |

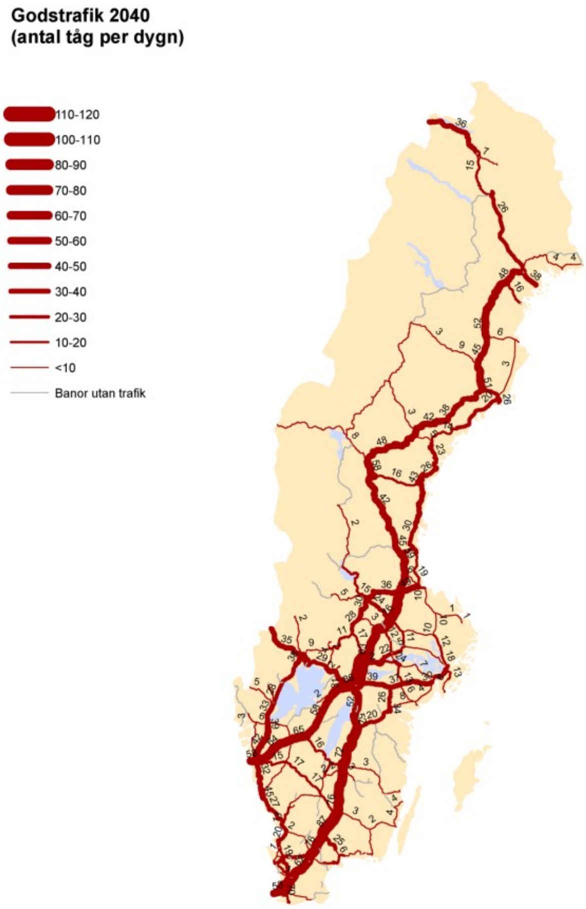



**Figure 3.5:** 2040 Future forecast for number of freight trains per day on the Swedish railway network [34]

**Table 3.4:** Exact calculations for the need of cargo transports. Emissions taken from [10]

| | | | | | | |
|---|---|---|---|---|---|---|
| **Flow Lulea and Kiruna** | max weight loco in ktons | Lulea | Kiruna | | | |
| Amount of carbon | | 4000 | 500 | | | **Total ammount of trains** |
| 2loco RE | 2.48 | 4.41891295 | 0.55236412 | | | 4.97127707 |
| 1loco RE | 1.24 | 8.83782589 | 1.10472824 | | | 9.94255413 |
| 1 RC | 1.05 | 10.4370515 | 1.30463144 | | | 11.741683 |
| 1MB | 2.05 | 5.34580688 | 0.66822586 | | | 6.01403274 |
| | | | | | | |
| | | | | | | |
| **Flow 1 Gävle-Gbg** | max weight loco in ktons | Gävle 1 | Gävle 2 | Stockholm Surroundings | Avesta | |
| Amount of carbon | | 2000 | 1500 | 3000 | 1000 | **Total ammount of trains** |
| 2loco RE | 2.48 | 2.20945647 | 1.65709236 | 3.31418471 | 1.10472824 | 8.28546178 |
| 1loco RE | 1.24 | 4.41891295 | 3.31418471 | 6.62836942 | 2.20945647 | 16.5709236 |
| 1 RC | 1.05 | 5.21852577 | 3.91389432 | 7.82778865 | 2.60926288 | 19.5694716 |
| 1MB | 2.05 | 2.67290344 | 2.00467758 | 4.00935516 | 1.33645172 | 10.0233879 |
| | | | | | | |
| **FLOW 2 MALMÖ** | max weight loco in ktons | Norrköping | Norköping 2 (two blue one green) | Mönsterås | Blekinge | **Total ammount of trains** |
| Amount of carbon | | 2000 | 3000 | 2000 | 1500 | |
| 2loco RE | 2.48 | 2.20945647 | 3.31418471 | 2.20945647 | 1.65709236 | 9.39019001 |
| 1loco RE | 1.24 | 4.41891295 | 6.62836942 | 4.41891295 | 3.31418471 | 18.78038 |
| 1 RC | 1.05 | 5.21852577 | 7.82778865 | 5.21852577 | 3.91389432 | 22.1787345 |
| 1MB | 2.05 | 2.67290344 | 4.00935516 | 2.67290344 | 2.00467758 | 11.3598396 |

# 4
# Discussion and conclusions

The results show a wide range of measures that are possible to implement for a more future proofed railway system. The system is complex, with many variables that can impact the capacity.

The railway lines that were chosen in chapter 3.1.1 were the most direct paths from sources to chosen harbours. Alternative routes with lesser capacity utilization but longer transport distances could be a solution for an increased freight transportation. What needs to be taken in consideration with such a solution is that smaller lines often have a smaller total capacity as they are often single lines.

The line segments identified as prone for disturbances and with a lack of capacity for a future traffic increase created by CCS transportation and other factors, consist of similarly track designs and are all located on the Swedish mainlines.
As the largest part of these lines are double tracked with meeting stations with adequate length for 750 meter long trains, improvement on these line segments would most likely result in larger infrastructure projects with a long time frame.

Some of the capacity increasing measures are the same for both single tracked and double tracked lines. As a first measure, more and longer meeting stations would be recommended to create more overtaking opportunities and increasing train length capacity on the line segment. Next solution would be to install more tracks on the line, and to separate (or further separate) different types of traffic. A solution applicable to double tracked lines with a lower capacity utilization with limited space would be to install a high speed switch to enable overtaking. A measure that is cost effective but put a high demand on planning of traffic flows. For single track lines, a space efficient solution for larger regions would be to extend or build new meeting stations with a length of 1500 meter to enable two trains on the side track.

Another measure to increase the capacity is to shorten the block sections. This will enable trains to run closer to each other. Although, shortening the block sections makes it harder to implement longer and faster freight trains. As the trains need to fit within the block sections and to run at speeds that enable short braking distances.

It is possible to increase the length of trains by train set-up. The existing locomotives have the capacity to carry far longer trains than the general length restrictions in Sweden. The limiting factors are the railway infrastructure and that braking percentage tables do not exist for trains longer than 730 meter. Achieving longer trains would increase the capacity, but it requires a lot of rebuilding of the current railway system as mentioned above.

Heavier trains are also possible to achieve from train set-up. The limiting factor is the railway infrastructure. Bridges and embankments would have to withstand the load from heavier trains. It is a rather expensive and extensive procedure to rebuild existing rail track for higher train loads. Therefore, it is more beneficial to do it when constructing new railways.

For international freight, higher loads are not relevant yet since most stretches in Europe have STAX 22,5 tonnes and STVM 8 tonnes which are the general values for Sweden.

It is possible to implement bigger reference profiles through rebuilding of the railway infrastructure. A switch from the general reference profile SEa to SEc would enable more freight volume on each train and thereby increase capacity. Since the Swedish railway was built to manage larger reference profiles it will not be too hard or expensive to implement.

Increased speed of freight trains is possible as long as the locomotives, running gear and brakes can handle faster speeds. Since noise and vibrations increase with speed, reducing precautions such as noise barriers and soil stabilization may have to be implemented.

Capacity could be increased if homogeneous speed were implemented. Although, this would be hard since speed limitations are different. Even if the speed of freight trains would be increased, passenger trains would still be faster and thus be limited if homogeneous speeds would be implemented.

Another mentioned solution is to fill the gaps between peak hours to increase the capacity, resulting in that trains would be running during night time. A negative side effect of this would be that less time is left for maintenance work. Less maintenance would resolve in breakage along with costly repairs and decreased capacity due to restricted usage of the track. Trafikverket has a continuous workflow to estimate future demands and the state of current capacity. If comparing the estimation for future quantity of freight traffic the impact of the new business area such as CCS, it will have the potential to be great impact. This might favor a larger investment in more project that will improve both passenger and freight operations with an economic incitement. If it is not considered, it can require a prioritization between freight and passenger.

# 5
# Further studies and recommendations

If the limits mentioned in the chapters before are reached, further improvements or innovations have to be made. An important aspect is the digitalisation of freight transport. One project to be mentioned here is the Digital Coupling System for Europe [35]. At this stage, research is still ongoing, but very promising. The advantages can be summarised as follows [35]:

- faster operations in the shunting yard,
- automatic shunting,
- increased payload,
- an improved braking system that requires electricity, contains control systems and works faster.

According to the first interim report [36], this system still needs to be improved, especially in regions where slush and ice can occur.
A research project that may also become interesting in the future is the Marathon project [37]. This examines the suitability of cargo trains that are 1500 meter long. The disadvantage of this project is the construction effort for single-tracks that goes along with it. Currently, the meeting stations are 750 meter long. These would have to be extended for such trains, which leads to very high costs. However, such a measure is cheaper than converting a complete line from single to double track. The problem, still, is the possible train weight of such a train configuration. This may change with the further development of brakes, couplings and locomotives.
Another topic that should be looked at in the future is the icing of wagon material. One possibility for de-icing would be a natural de-icing by means of a desposition, in which the wagon material passes from cold to warm areas in one cycle and vice versa. It is important to investigate whether this can guarantee year-round availability. The second possibility would be to set up facilities in the north where the wagon material can be de-iced. It would make sense to have this near the port, as most of the wagon material passes through there, but the space may not be available. Furthermore, it could not be investigated more precisely when the seasonal peaks are. Therefore, parking problems may occur if not all the wagons are needed. Accordingly, storage possibilities that may be located inland would have to be discussed, as space at the ports may be limited. In this context, a more detailed investigation into the wagon material could also be beneficial.

The wagon material may be useful for transport from the port to the interior, as this work is limited to the additional transport needs towards the port. Furthermore, multi-use could compensate for parking problems outside peak times. Multimodality should also be investigated in the course of the wagon study. Not every company has a rail terminal or can afford one, so it would be interesting to transport the $CO_2$ by trucks to loading stations in order to reload it there without a major operation. In the course of good operability, the loading and unloading process should be looked at more closely. Questions in this context could be:

- How can an optimal unloading process, in the best case automated, be presented?
- Is a loop concept possible at ports so that a train can be unloaded and returned without shunting?
- Is an electric overhead line possible and permitted in the unloading area?

Overall, this project is still in its early stages and there is a need for further research.

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