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A simulation study of the cost and efficiency of 90+ ton trucks in Sweden

Examining potential and barriers within the forest industry in Sweden, in regards to heavy trucks

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Civilingenjörsprogrammet i system i teknik och samhälle

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Abstract

This thesis had the goal to investigate the potential of 90+ ton trucks in Sweden. As of current, the highest allowed weight on public roads is 74 ton. A few research questions were formulated in order to capture the most important aspects of the system in which these vehicles operate. The research questions were what the potential economic savings could be, what the environmental improvements could be, where these vehicles best operate and which barriers that exist for these vehicles to be successfully deployed.

The method has consisted of a literature study, interviews with experts and building a simulation model to see if the efficiency observed in some cases would be applicable to other cases as well.

The results from the simulations show the same positive trend toward bigger trucks even with more and longer routes driven. This was the case even when prices for fuel were set to different values in order to see its effect on the relation between the compared trucks. It was also shown that the heaviest vehicle, 98 tons, still would be more effective if its cargo weight was reduced by 10%.

The conclusions from the study is that the BK4 road network that exists in Sweden need to be expanded as well as bridges in the network being analyzed and reinforced to handle proposed gross weights in the future. For the 90+ ton trucks themselves, rigid flows of biomass like in those cases where terminal driving occurs are the most suitable cases for the trucks due to the predictability of the high biomass flow.

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Acknowledgements

This thesis marks the end of my full time studies at Uppsala University and my master's program in Sociotechnical Systems Engineering (STS).

During my writing of this thesis I've become more and more aware of how little one knows about a subject until you start researching it and I would like to give a huge thanks to both my subject reviewer Per Lötstedt, for making sure I was on the right track and for answering my questions fast. I would also like to thank my two supervisors at Skogforsk, Anna Pernestål and Daniel Noreland. They both have helped me tremendously in understanding what kind of system the forest industry is and what kind of results that would be useful to get.

Erik Edlund June 2024

Populärvetenskaplig sammanfattning

I Sverige finns det mycket skog. Skogsbruket har i Sverige varit en väldigt etablerad industri och mycket forskning har gjorts inom många av de områden som berörs av denna industri.

Man har nyligen infört en ökad laglig gräns för total vikt till lastbilar, 74 ton. Detta har skett genom det så kallade ETT projektet, som har haft som syfte att undersöka potentialen av “En Trave Till”. Detta har skett eftersom man sett en stor potential i att kunna frakta mer lass per bil och på så vis effektivisera transporter. I Sverige är skogsindustrin en av de större industrierna då värdet av dess exporter var 186 miljarder år 2022.

Denna studie har haft som syfte att undersöka vilken ekonomisk och miljömässig nytta man skulle kunna få genom att köra med ännu högre bruttovikter än vad som är lagstadgat idag. Dessutom har barriärer, faktorer och olika scenarion där de tyngre bilarna kan köra varit viktiga att identifiera för kunna ge en så nyanserad och rättvis bild som möjligt. Dessa har varit delmål för att kunna motivera vilka delar som är mest relevanta att titta på framåt. De bruttovikter som undersökts i denna studie har varit 64,74 och 98 tons fordon.

För att kunna ta fram meningsfulla resultat gjordes först en litteraturstudie där det visade sig att det finns väldigt många faktorer som spelar roll. Dessutom gjordes en mängd intervjuer med experter från ETTs styrgrupp med bred kunskap inom området High capacity transport (HCT), det vill säga de bilar som är tyngre än traditionellt vägande bilar.

Med avgränsning baserat på fynd i litteratur och lärdomar från intervjuer gjordes en simuleringsmodell där körningar under ett till flera år testades för att se vilka utfall som skulle kunna ske. Data togs och filtrerades för de rätta vikterna, från ett redan etablerat fall. Sedan skapades fördelningar av lastfyllnadsgrad för olika fordon för att kunna få en bild av fordonens effektivitet med last i åtanke i en ny miljö. Två scenarion testades där ett var terminalkörning fram och tillbaka mellan industri och lastplats, medan det andra scenariot hade många upphämtningsplatser och två industrier som behövde materialet. Utfallen från dessa har sedan jämförts och olika enheter har tagits fram för att kvantitativt redogöra för vilka besparingar som skulle kunna ske ifall man implementerade ännu tyngre lastbilar i de scenarion som undersökts.

Slutsatserna från denna studie är att det finns besparingar att göra även i mer komplicerade fall med fler upphämtningsplatser, men där flödet av biomassa inte är för varierande. Både ekonomiskt och utsläppsmässigt gav 98 tons fordonet en förbättring mot de 74 och 64 tons fordonen. Andra slutsatser är att BK4 nätverket i Sverige behöver utökas för att gynna ännu mer effektivisering för de ännu tyngre fordonen. Inom BK4 nätverket behövs även fler undersökningar av hållbarheten hos broar och deras klassificering för att skapa så få flaskhalsar som möjligt för transporterna som körs.

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Nomenclature

Cargo weight: how much mass a vehicle carries.

Gross weight: total weight of the entire vehicle.

Wood chips: small wood pieces. Used in heating plants among other uses.

High capacity transports (HCT): Higher length, volume and/or allowed weight for trucks. Typically higher than 64 ton.

En Trave Till (ETT): The project, one more stack, which has had the aim of looking at increasing maximal allowed weight and allowed length of vehicles on Swedish roads.

Traffic flow: Interactions between every actor on roads and the roads' infrastructure in order to minimize congestion problems and achieve efficient movement of traffic.

Vehicle-kilometer: Determined by multiplying the number of vehicles on a given road or traffic network by the average length of their trips measured in kilometers.

Payload-distance: how much payload that has travelled a specified distance.

Ton-kilometer: Ton multiplied by how many kilometers it has been transported.

1. Introduction

The forest industry has existed in Sweden for more than 200 years [1]. It has a profound economic importance to the country and in 2022, the industry exported products to a value of 186 billion SEK [2]. In order to transport timber, wood and woodchips, heavy trucks are needed.

In 2009 the ETT project started in northern Sweden [3] with testing of vehicles. The initiative to research the subject was however already introduced in 2006 [3]. The project has had the goal of researching what increased allowed gross weight might bring in terms of effectiveness in transportations. After numerous tests and analyses conducted by organizations such as Skogforsk and the ETT project, it became permissible in 2018 to operate truck configurations weighing up to 74 tons on large parts of the Swedish road network [4]. This has been crucial for the forestry industry, where the amount of goods that can be transported is generally limited by weight. Within these contexts HCT is used which means using truck configurations that are heavier and longer than normal. HCTs has the potential to reduce fuel consumption per transported ton, and the number of trucks needed. Historically a few changes to allowed weight has happened. In 1966, 37 tons became legal and from there a few other years increased the weights as follows. In 1974: 51,4 tons, in 1990: 56 tons, in 1993: 60 tons, in 2015: 64 tons and in 2018: 74 tons. Length as also increasd from 24 meters in 1972 to a maximum of 34,5 meter in 2020 [5, p. 6-7]. The next step is even heavier vehicles, over 90 tons. Currently, tests are being conducted with wood chip transports in Södertälje [6], and additional tests are planned to explore technical perspectives. While there is great potential to further save fuel with 90+ ton vehicles, there are several challenges: accessibility is limited (for example, by bridges) [7], sufficient cargo volumes are needed for efficient transport, and fuel consumption increases for empty transports (relevant if, for example, the transport needs to return empty) [6]. Therefore, it is now relevant to explore the potential for economic savings and CO2 reduction with 90+ ton configurations in the forest industry.

There have been studies on the subject of HCTs, where results have shown a positive trend towards economic profit and environmental impact reduction when making these transports larger [8]. These facts have come with caveats in some cases where max cargo weight, degree of use, road conditions and category of wood, play a role in the efficiency [9]. The subject has been well studied in both Finland [9] and Sweden [3] where the forestry culture is very similar.

The thesis is conducted within the framework of the ETT project at Skogforsk, and the results will be presented to the ETT steering committee. The purpose is to get a clearer picture of the future of HCT and what that future will entail.

1.1 Research questions

With the introduction of the 74 ton truck some consequences for the road infrastructure and the industry has followed. In order to introduce even heavier trucks on the Swedish roads one needs to make sure there are relevant and strong reasons for doing so. To do so, research questions were formulated in order to get a better grasp of what kind of results or information that would help advance the field of HCTs.

- What is the potential (economical and emissions) of using 90+ ton carriages for road transports in Sweden, and how could one calculate these results?

In order to answer this question in a more applicable way a few sub questions were set so that the potential could be given within a delimited area.

  - What barriers exist in order to drive 90+ ton carriages?
  - What factors determine if 90+ ton carriages are effective or profitable?
  - In what cases are 90+ ton trucks feasible to use?

1.2 Delimitations

This study aims to highlight areas of potential and areas of limitations on what could be done regarding implementing HCTs heavier than 74 tons. This means the study will highlight a number of important factors that may have an impact on the transport system. All factors will not be used when simulating different cases due to what the scope of the thesis is, which is about the physical potentials of the vehicles, but these factors are nonetheless relevant to keep in mind if potential implementation of heavier HCTs is considered in the future. One aspect of the system not touched upon at all is the profit and negotiation between buyer and haulage companies and what their respective contracts are.

2. Previous studies

Much research has been done within the forest industry and is presented in the next ten sub-chapters, Ten subjects will be presented that are relevant to understand the whole system. It also helps future implementation to give a general direction of where to put a lot of focus.

2.1 Efficiency in larger trucks driving woodchips

Some research has compared the efficiency of heavier and lighter trucks. Findings show that the heavier vehicles are more efficient, although not always due to cargo weight [6]. In the study ETTdemo flis [6], the commodity transported was wood chips. The distance traveled was approximately 20 km long. The study [6] focused on a truck with a maximum gross weight of 98 tons, with 66,1 tons as maximum cargo weight and 198 m^3 in capacity. They compared it to 74 tons with 147 m^3 and to 64 tons with 140 m^3. They used diesel as fuel during the study [6]. They stress the importance of utilization and the cargo weight on the trucks, since these factors determine if the bigger trucks are worth an economic investment. The heavier trucks come with a higher total cost of operation and therefore have higher requirements for how much they need to deliver and be used. The study [6] found that in order for the 98 ton truck to be more efficient than both 64 and 74 ton trucks, they needed to weigh no less than 80 tons, gross weight. In tables one and two, mean cargo weight, fuel consumption for different cargo weights, ml/(ton*km) and mean velocity are presented for two road types, urban and highway.

Table 1: Results of the study on wood chips. Load weight and fuel consumption from the five weeks the study was in operation [6].

			Bränsleförbrukning	
Max bruttovikt	**Lastvikt, ton**	**Lassfyllnad, %**	**lit/100 km**	**ml/tonkm**
64 ton	41,88	100	64,23	32,53
74 ton	42,98	91,9	78,65	38,14
98 ton	60,95	94,8	90,37	29,84

Table 2: Fuel consumption per 100 km and ton km respectively for the three types of vehicle combinations, split into road type and loaded/unloaded in [6].

<table>
<tr><th colspan="2"></th><th colspan="3">Landsväg</th><th colspan="3">Tätort</th></tr>
<tr><th>Max bruttovikt</th><th></th><th>l/100 km</th><th>ml/tkm</th><th>Medelhast. km/h</th><th>l/100 km</th><th>ml/tkm</th><th>Medelhast. km/h</th></tr>
<tr><td rowspan="2">64 ton</td><td>tom</td><td>3,7</td><td>-</td><td>85,2</td><td>5,3</td><td>-</td><td>30,4</td></tr>
<tr><td>lastad</td><td>5,6</td><td>13,6</td><td>83,2</td><td>8,9</td><td>21,7</td><td>38,1</td></tr>
<tr><td rowspan="2">74 ton</td><td>tom</td><td>3,9</td><td>-</td><td>83,6</td><td>5,4</td><td>-</td><td>42,2</td></tr>
<tr><td>lastad</td><td>6,1</td><td>14,6</td><td>85,2</td><td>11,7</td><td>28,0</td><td>38,7</td></tr>
<tr><td rowspan="3">98 ton</td><td>tom</td><td>3,9</td><td>-</td><td>79,6</td><td>7,8</td><td>-</td><td>42,6</td></tr>
<tr><td>lastad < 90 t</td><td>6,6</td><td>13,3</td><td rowspan="2">76,7</td><td>14,3</td><td>28,7</td><td rowspan="2">35,3</td></tr>
<tr><td>lastad ≥ 90 t</td><td>8,5</td><td>13,0</td><td>11,1</td><td>16,9</td></tr>
</table>

Reading from table 1 and 2 the unit most relevant to determine the effectiveness of the trucks in the study is ml/(ton*km) which is a good measure of fuel used per vehicle-kilometers and how much material that has been transported. It would appear that the heavier cargo weights would be beneficial due to the cost being 20% more and being able to carry 40% more cargo. At least according to the results from the study which gave the following results: 326 kr/10km and 31,2 kr/ton for 64 ton trucks, 365 kr/10km and 34,0 kr/ton for 74 ton trucks, 443 kr/10km and 29,1 kr/ton for 98 ton trucks[6, p. 27]. These numbers show a 20% increase in cost (kr/ton) for the 74 ton truck compared to the 98 ton one which both show the complex relation when going heavier as well as the effectiveness gained. The complexity comes from the fact that the 74 ton truck were not more effective than the 64 ton truck. The reasons given in the study for this was due to not being able to fill the truck to the desired capacity due to volume restrictions [6].

2.2 Truck performance assessment

Truck performance has been studied in “Performance assessment of high capacity trucks: Understanding truck selection and deployment economics” [9] where a few key factors were recognized in order to evaluate how cost effective bigger trucks are. Important factors were: truck utilization and seasonal variability in regards to driver attitude and truck driving behavior. The study compared trucks with more traditional weights to HCTs with a maximum gross weight of 76 tons and evaluated them on three different routes driven. Their conclusion was that the heavier 76 ton trucks were more efficient than the traditionally weighing trucks. The bigger trucks had space for 104 pallets and the smaller trucks, space for 75. This study helps to make the case that heavier trucks are more effective in terms of operation than smaller trucks. However, factors such as season can affect the efficiency. “The size advantage HCT has over traditional [trucks] translates into moderately higher revenue and profitability based on the available data” [9]. In one case the HCT truck had even lower fuel consumption than the lighter truck, which in their case could be due to driver behavior, but they do not specify that driver behavior was the reason. These findings contribute to a complex and positive trend when utilizing bigger trucks. Worth mentioning is also that they only looked at trucks up to 76 ton. These results contribute to a good foundation for looking at implementing HCTs.

2.3 The BK4 road network and road infrastructure

Since the creation of the ETT-group, a set of changes have been made to the Swedish road and vehicle regulation to accommodate the introduction of HCTs [10].

On Swedish roads, a classification system called BK is implemented. BK1 is the default road classification for state managed roads and all other classifications are exceptions. A BK3 road is only suitable for a maximum of 37,5 tons, BK2 for 51,4 tons, BK1 for 64 tons and BK4 for 74 tons [11]. The maximal axle load for all except BK3 is 10 tons and for BK3 it is 8 tons [12].

Studies have shown bottlenecks and some limitations on how the road network can be used by truck transports, from one place to another [12] [13]. Being able to use the most optimal paths for transporting goods is imperative to make a good profit on the transports. This highlights the importance of the road infrastructure and its consequences if not managed correctly.

In order to be able to use HCTs, an adequate road infrastructure is needed. Höök and Asmoarp [12] identified bottlenecks for the heaviest trucks in Sweden. Their finding showed that the bottlenecks were the links missing in between BK4 roads and the main barriers for establishing HCT corridors lie in terminal establishment and management costs. They also showed some of the potentials of HCTs. “Results showed there was annual potential for 25 HCT corridors throughout Sweden to employ 20 90 t trucks to transport 2.5 Mt of roundwood, reducing up to 5500 t[on] of CO2 and €3.1 M in fuel costs “ [12].

Table 3. Potential reductions in CO_2 emissions and fuel costs (after superimposed terminal costs) for the terminal supportive via-corridor transports [11].

National Area	National Area Name	Emission Reduction Potential, t CO_2	Cost Reduction Potential, Thousand €
SE11	Stockholm	-	-
SE12	East middle	247	20
SE21	Småland and the islands	1076	344
SE22	South	-	-
SE23	West	529	132
SE31	North middle	1699	358
SE32	Middle Norrland	940	110
SE33	Upper Norrland	1043	299
sum		5534	1263

Some relevant findings for this study are the summaries relatively recent in time. The result [14] for the years 2017-2020 gives a good picture of today’s relevant findings. The study [14] goes through what the ETT project is about and what role the BK4 road network has in regard to the transports on Swedish roads. As can be seen in Figure 1 the road network has been regulated to handle BK4 to a degree. More roads are planned to expand the network.

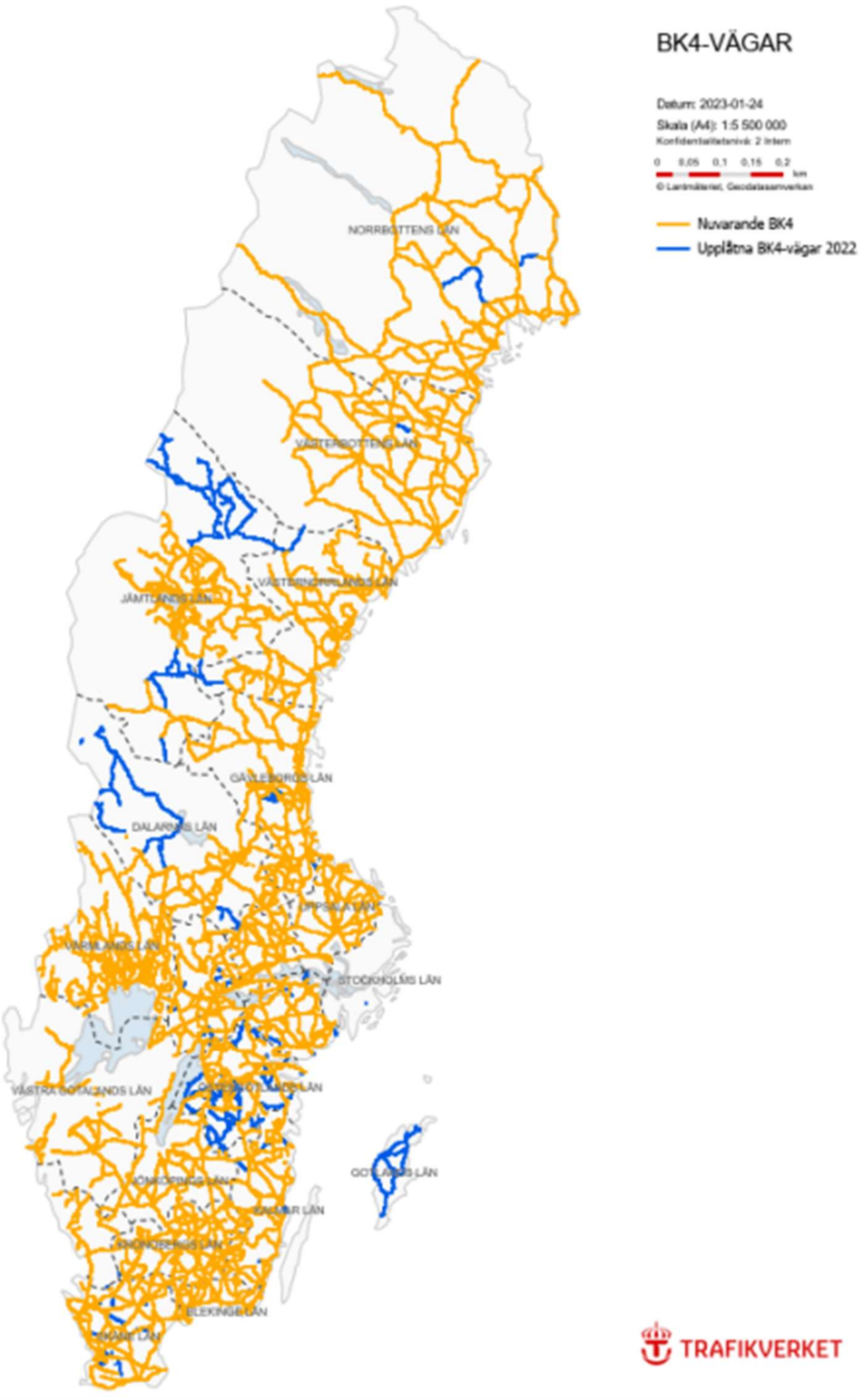


Figure 1. BK4 road network in Sweden. blue lines are roads approved 2022 [11].

2.4 Road infrastructure and vehicle fleet combinations

The report "Transportkostnader och virkesflöden" [7] regarding combinations in the vehicle fleet, demonstrates just how important the road infrastructure and utilization ratio is, if the bigger trucks are to be more efficient. This is because without the proper amount of available roads and the proper amount of transports the ticking costs of bigger trucks are indeed greater than that of the smaller trucks. The findings can be demonstrated with Table 4,5 and Figure 2.

Table 4. Number of vehicles of each type in the different scenarios from the study [7]. Each scenario has been done for 3 repetitions.

	Antal fordon per bruttoviktsklass				Totalt antal fordon
Scenario	64	70	74	90	
S1	2	5			7
S2		7			7
S3	1	3	3		7
S4	1	3	2	1	7
S5		3	2	1	6
S6		4	1	1	6
S7		1	3	2	6

Table 4 demonstrates the number of vehicles of different weights used in the study [7].

Table 5. Costs in kr/ton at the industry gate for all the scenarios [7].

Scenario	Kr/tonkm	Transporterad volym	Kr/ton
S1	1,375	249 806	98,79
S2	1,406	255 772	99,03
S3	1,393	250 163	97,75
S4	1,392	245 558	95,99
S5	1,412	245 325	98,71
S6	1,408	247 529	97,01
S7	1,392	200 700	104,77

In Table 5 the third column shows how much mass that was transported given in m^3. Even though S4 and S7 has the same kr/(ton*km), S7 still has a much higher kr/ton. This is due to the volume delivered which for S7 was more than 40 000 m^3 less than any other scenario. The reason is that there was a shortage of vehicles in that scenario that could transport timber on BK1 and narrow BK4 roads, since the 90 ton trucks in the study were assumed not to be used as either 64- or 74-ton trucks[7]. Issues with the road infrastructure can be seen in Figure 2 where only part of the road network has been regulated to BK4, which means that trucks can not go all the way into the industry mill with weights higher than 64 tons.

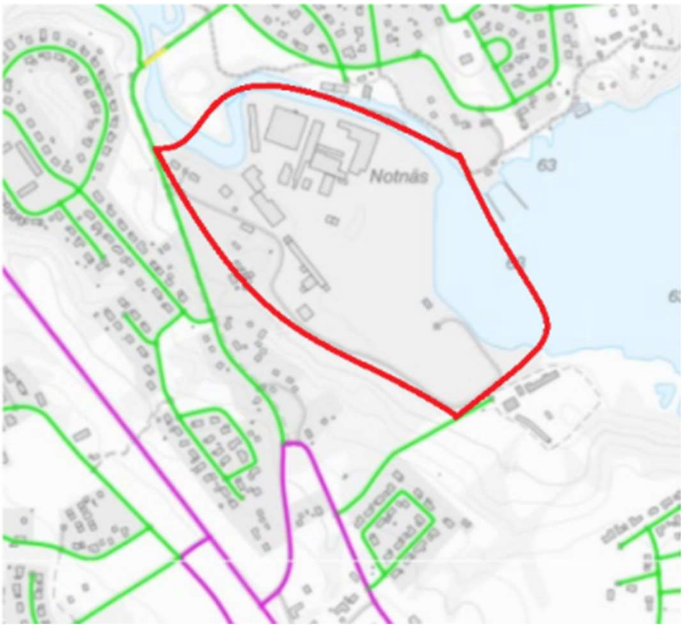


Figure 2. Load classification on the entrance roads to the timber mill in Torsby (Notnäs). Pink is BK4 and green is BK1. The mill is marked inside the red markings.

2.5 Timber flows

In order to understand of how much resources the industry transports and what the theoretical maximum amount of products that could be shipped with HCTs is, some studies were looked at. According to "Skogsbrukets vägtransporter 2020" [15], in 2020, 34.2 million tons of timber, 31,7 million tons of pulpwood, 6,2 million tons primary forest fuel, were transported.

*Table 6. Transported quantity, ton*kilometers, vehicle kilometers, and average transport distance for forestry transports in 2020, shown by assortment (timber, pulpwood, and primary first fuel) and for total biomass [15].*

Assortment group	Quantity (million tonnes)	Tonne-kilometres (millions)	Vehicle kilometres (millions)	Average transport distance (km)
Timber	34.2	3 166	129.4	92.7
Pulpwood	31.7	3 050	131.0	96.1
Primary forest fuel	6.2	387	24.1	62.1
Total biomass	**72.2**	**6 604**	**284.5**	**91.5**

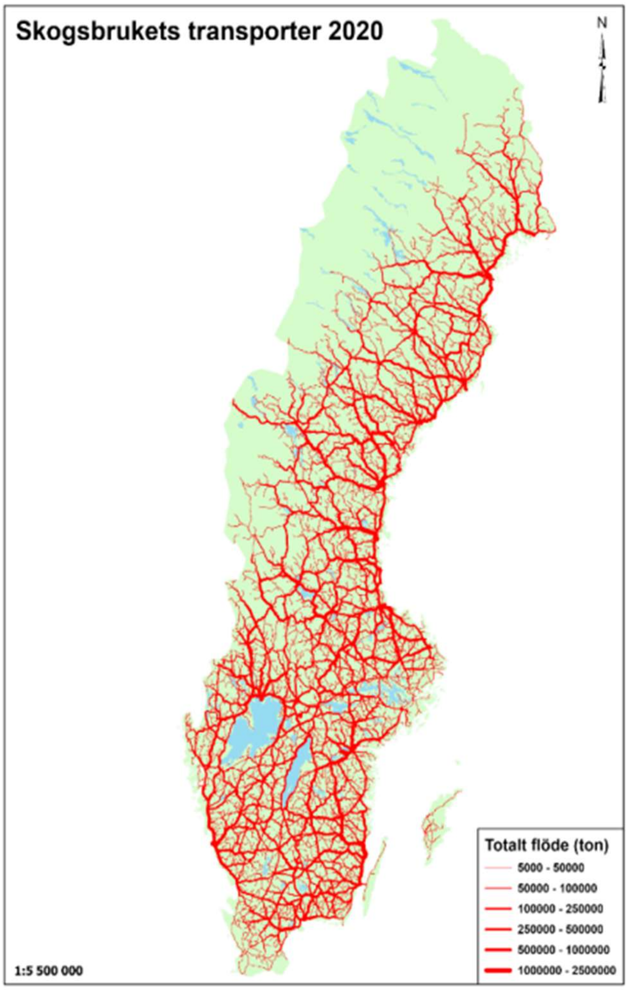


Figure 3. Flows of biomass along the Swedish road network, 2020. Line width is proportional to the transported quantity.

Figure 3 shows how much biomass was transported in Sweden, in 2020. Figure 3 and Table 6 give good insight into what magnitude of biomass that is being transported in Sweden and thus approximates what kind of maximum roadwork there is in Sweden. Where there is the most mass being transported would also be more suitable for higher weights. From Figure 3 one can conclude that the area around Karlstad, the Norrland coast and the area around Gävle could be areas where utilization of HCT could be higher due to the higher amount of transports.

2.6 Road wear

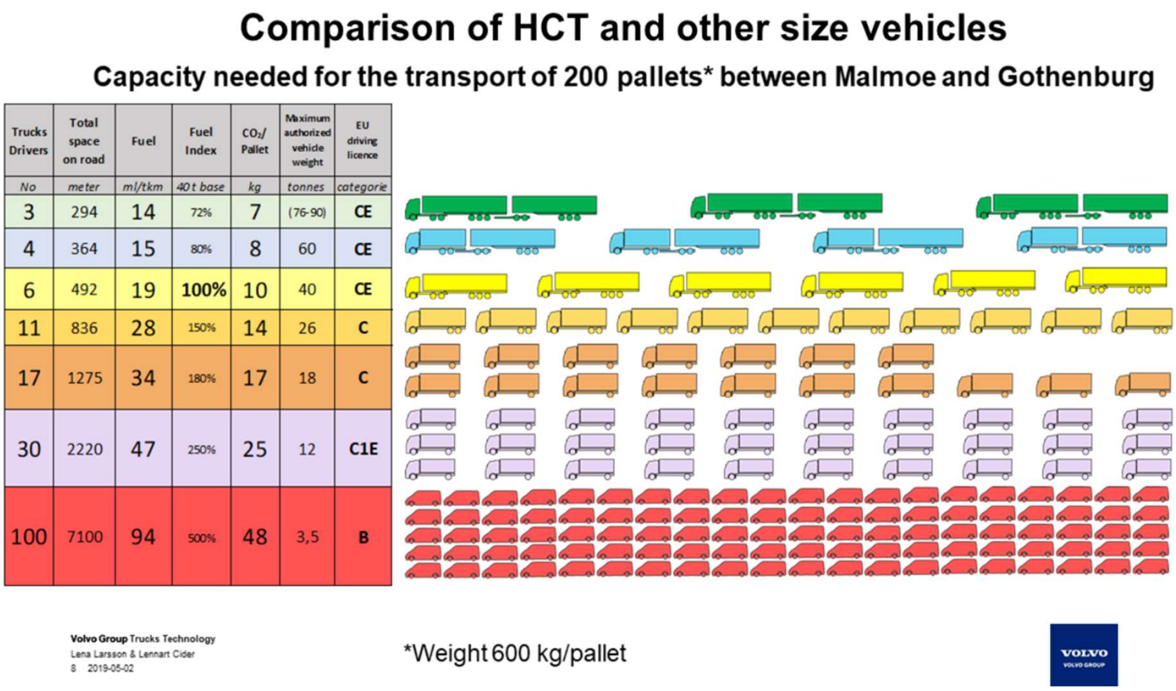
The study "HCT-fordon för rundvirkesvirkestransporter" [16] goes through wear and tear on the roads, cargo density over the year and presents estimates of capital costs. The study also points out the major downside of bigger vehicles. For example, they need to be driven with more load and more often to be more profitable. The bigger trucks are dependent on access to the BK4 road network to utilize their bigger size. They also showed how fuel and cost are affected by increasing truck allowed weight up to 74 tons.

Even though heavier vehicles wears more on tires, the study [16] speculates that the higher cargo weights will compensate for the increased wear. The wear difference is larger between different sized trucks in the scenarios where they start and stop, which is also when one could observe a slightly higher machine wear [16]. For the actual road wear, the differences at least with paved roads, is little. The different wears point to a more complex image than that just the gross weight is responsible for higher wear. More studies are needed in order to further confirm it.

2.7 Needs from Haulage companies

According to Transportarbetaren [17] the haulage companies have a shortage of drivers and need 50 000 new ones in the coming ten years. This is relevant when looking at the advantage of bigger trucks, outside of the technical or economical aspects, namely easing the mentioned shortage. In both [18] and [19] Lena Larsson and Lennart Cider present data and statistics from ETT DUO2 comparing different trucks and their different characteristics. The most notable comparison can be seen in Figure 4, where a reduction in needed drivers and used up road space in meters can be seen between 60 ton trucks and up.

Figure 4. Comparison Figure from [18] and [19]



Trucks Drivers	Total space on road	Fuel	Fuel Index	CO_2/ Pallet	Maximum authorized vehicle weight	EU driving licence
No	meter	ml/tkm	40 t base	kg	tonnes	categorie
3	294	14	72%	7	(76-90)	CE
4	364	15	80%	8	60	CE
6	492	19	100%	10	40	CE
11	836	28	150%	14	26	C
17	1275	34	180%	17	18	C
30	2220	47	250%	25	12	C1E
100	7100	94	500%	48	3,5	B

2.8 Aerodynamic factors

Studies like "Timmerbil utrustad för minskat luftmotstånd och lägre bränsleförbrukning" [20] have looked at potentials for improving aerodynamic structures on trucks to make them more effective. In the study [20] they mention that Linköping University tried a few simulations displayed in Figure 5. From them the researchers decided on one configuration, which was based on effect, production cost and practical useability. The chosen one was a so called “skirt” shown in Figure 6. The trailer was also equipped with wind deflectors placed in front of the first axle.

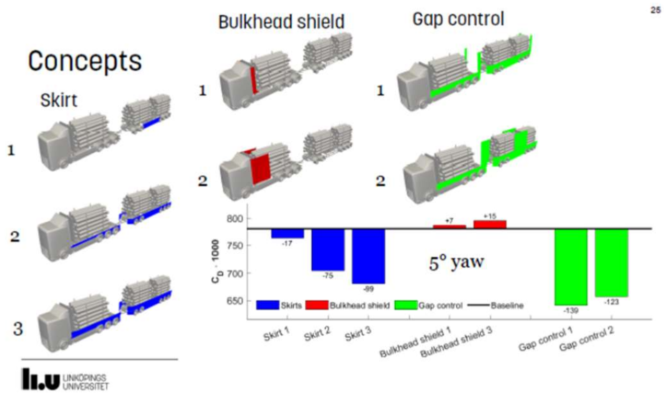


Figure 5. Examples of results from the simulations. On the far left are various forms of skirts, where the results in terms of reduced air resistance are shown by the three blue bars. Covering between the cabin and the first stack appears to be less successful and rather increases air resistance somewhat (red bars). Skirts in conjunction with wind deflectors between the truck and trailer and at the rear of the trailer (gap control) appear to be the most effective, but also the most difficult to implement practically.

Figure 6. The aerodynamic skirt close up.

The study [20] had three configurations during their practical trials. One standard without any aerodynamic improvements, one with the skirt and nothing more and finally one with the skirt + the bunks and stakes manually stacked in the front of the trailer. The results from the study are displayed in Table 7 and shows the difference between the vehicles where C_d is the air resistance coefficient and A is the area. The results from the study [20] show that the skirt reduced C_dA with 0,2 m^2 and the bunks reduced C_dA with 0,5 m^2. What this tells us is that these changes made the vehicles more aerodynamically efficient.

Table 7. Results from "Timmerbil utrustad för minskat luftmotstånd och lägre bränsleförbrukning" [20].

Rolling resistance	C_dA for Skirts+ bunks	C_dA for Skirts	C_dA for Standard
0,0074	7,5	8,0	8,2

2.9 Electrification

Several business models have been proposed and how these could potentially change if the systems became more electrified [21]. At Skogforsk there have been studies on the electrification of HCTs. One notable study is a master thesis from Uppsala University by Albin Werre [22] where he looked at the electric need of big trucks from an event based simulation model. The thesis concluded that around 60% of trucks in the specified case could be electrified without major changes to route planning or transport patterns.

A major study similar in its goals to this thesis is "Elektrifiering av skogsbrukets vägtransporter" [23] which treats barriers and opportunities for the electrification of the transport system in regards to the forest industry. The study [23] had several parts to reach its conclusions. The parts consisted of Albin Werres master thesis [22], some workshops as well as a literature study of what work that had already been done. Some barriers identified for the electrified higher weight HCTs were higher investment costs, short reach and that the system becomes more complex than with just diesel trucks since new payment models and contract models are needed to fully incorporate the new electric vehicles.

2.10 Full cost analysis of HCT vehicles

In order to understand costs within the forest industry it is necessary to understand company economic principles and well established values for machine costs. This has been done in "HCT-kalkyl" [24], where multiple calculation models were implemented into one calculation formula for 60-, 64- and 74 ton trucks. The study [24] laid out all relevant factors for cost prediction with costs like investment, load fill rate, km driven, salary and many more. The calculation model had the goal of combining several relevant industry actors' calculation models into a more expanded calculation model for comparing different vehicles effectiveness.

2.11 Summary of previous studies

The studies mentioned in the ten sections give a broad background to the system that HCTs operate in. They give insight into cost calculations for HCTs that are relevant when calculating what affects the costs. The ongoing electrification of the system has previously been studied and the effect needs have been calculated for different scenarios. Biomass flows has been shown for a more complete picture of the forest industry. What configurations that could increase the aerodynamic efficiency has also previously been studied and analyzed. Different sized vehicles have been compared in terms of space on road and the number of drivers needed. All the previous research gives a basis for understanding and analyzing the system which HCTs operate in.

3. Method

In order to answer the general questions posed in this thesis a mixed method approach was used in order to narrow down and get a grasp of the posed questions. It was chosen due to its ability to help answer the research questions with sufficient depth and breadth [25, p. 25-36]. In Table 8 different aspects of the thesis are connected to certain methods to make the argument that they are relevant to use in this context.

Table 8. Map of what contributions the different methods bring to answering the posed research questions.

Contribution to research questions	Interviews	Literature study	Simulation model
Relevant factors and barriers	X	X	
Deep knowledge about HCTs	X		
Results about efficiency		X	X
CO2 and economic potential of HCTs		X	X
New conclusions about cases			X

3.1 Interviews

To better understand the systems involved with HCT and have a good starting point of what to work on, interviews of board members in the ETT group were conducted. See appendix A for the questions asked. A total of ten interviews were held. All of the people in the ETT group have expertise and deep knowledge about HCTs. Representatives from Skogforsk, Volvo, Billerud, Skogindustrierna, SCA, Trafikverket, Scania, Sveriges åkeriföretag, Stora Enso, Transportstyrelsen, Sveaskog, Riksförbundet enskilda vägar, Södra and Holmen are part of the group. The ETT-group represents practical experience from years of operation within transportation and HCTs.

The interviews fell under the definition of semi-structured interviews. "When conducting semi-structured interviews you as an interviewer have a list of themes and questions that are to be discussed during the interview, a so-called interview guide. Both the content and the order of these questions and themes can vary, [from] interview to interview" [26, p.163]. This was exactly how the questions were handled during the interviews. With “Marknadsundersökning en handbok” [26] as help when choosing how to conduct the interviews it seemed to help capture the sought after knowledge the individuals possessed.

The questions were structured to be open ended. This was due to the openness of the project. In order to capture the thoughts of the ETT-group regarding the system these trucks are used in, open ended questions best accomplished this. According to “marketing research“, “Open-ended questions have the advantage of providing full answers and exploring issues that are new to the researcher” [27, p.194].

Since the questions were asked with the intention of getting a good grasp of the subjects brought up, some questions were avoided due to the subject already being brought up in a previous question.

The answers to these questions were summarized in a document and were analyzed in order to extract some key points from the competence that exists within the ETT-group.

3.2 Literature study

The literature study has consisted of collecting studies and results in a lot of different fields regarding using HCTs. Using information from the interviews it became easier to narrow down searches for the most relevant studies. Using studies as inspiration for the type of results that might be most relevant to look for made it much easier to implement the structure model most appropriate for the results searched for. Many of the addressed upon subjects have not been used later in the simulations of this study. However, the findings from all analyzed studies help to answer the questions posed by giving a more complete picture.

3.3 Modell and simulation

The models in the study were based on cases where the flow of resources was very rigid and then applying these flows to broader cases with multiple off and on loading places in order to potentially see any difference in performance in these cases compared to the simpler case. The model and simulation was event based because having a time based model was deemed unnecessary due to the intervals between driving and loading up the trucks.

3.3.1 General simulation description

During simulations, two cases were used. The general code for them both were the same with differences in driven road. The main differences between the original ETTdemo flis [6] and this thesis were the following

- A normal distribution was added to the regression model for fuel consumption.
- Filtering the weights in the data to only drive with legally allowed weights.

- The assumed driving distance for all three vehicle types was approximately the same.
- The days driven in a year were set to 310 for all vehicles.

The code in MATLAB was divided into a main model code, a truck class and classes for all different industry loading places. After putting distributions of weights and their respective fuel consumption into a vector to be used in the model, different conditions were set depending on the type of vehicles (64,74 and 98 ton). Fuel consumption and time it takes to load were all determined according to what vehicle was driven. Distance of highway and urban road was set depending on route driven. The next event in the model was the vehicle driving to the loading place and consuming both time and fuel. Then loading the cargo from the distribution vector onto the truck with both fuel and time ticking. Lastly driving the cargo to the goal destination and unloading it, writing in all calculated numbers like fuel, time and distance into a vector to be stored and used. In Figure 7 one can see a visual representation of the events in the simulation.

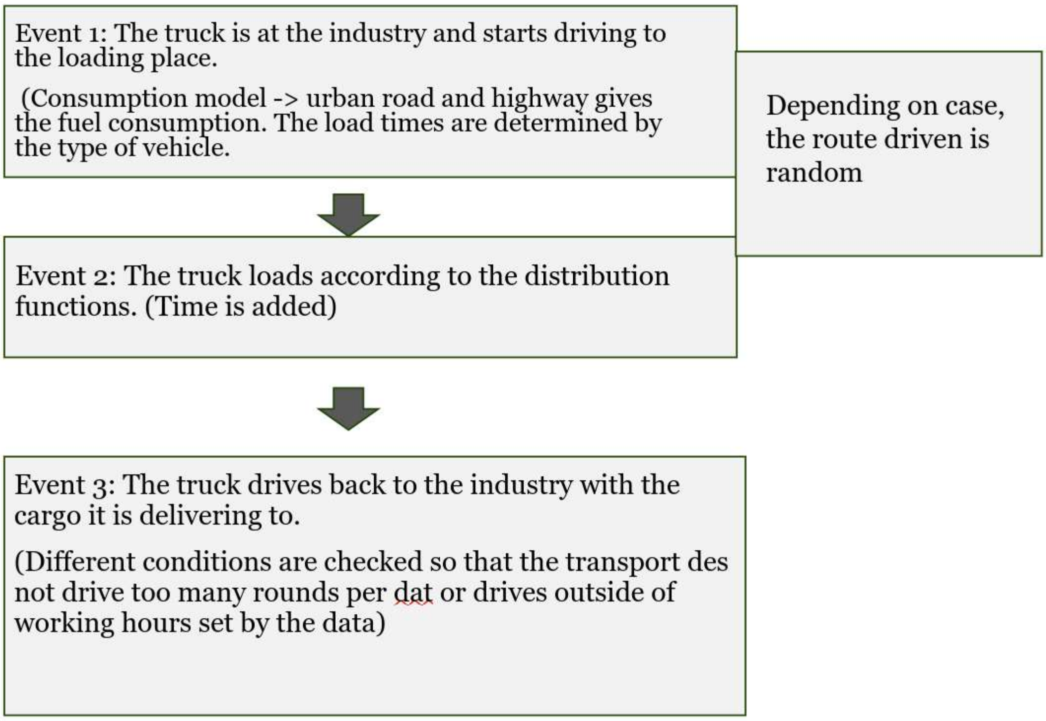


Figure 7. A visual representation of the event based simulation model

Several conditions were set in order for the simulation to be more realistic. These were time cut offs for the working days which were set to between 06:00 and 19:00 and operations stopping if the wood chip supply happened to be empty. The maximum allowed trips per day was set to 9 and the least amount to 4. The simulation looped over several years. At first, five years were tried but since it was mentioned in ETTdemo flis [6] that trucks had an approximate lifespan of 1 000 000- 1 400 000 km, ten years was chosen instead to get more data points, a more stable mean value and also drive closer to the lifespan distance.

3.3.2 Data

Data from ETTdemo flis [6] was used in order to expand upon the findings from that study. The data available from that study was costs for different services, cargo weights of every transport and time of departure of the vehicles. The data was structured according to the time, dates, the transports that occured, gross weight and empty cargo weight. Fuel consumption and different costs were taken from ETTdemo flis's [6] calculations. From the data, truck cargo weight was determined to be the most appropriate factor for efficiency when trying to simulate bigger trucks.

The data was filtered due to some weights being over the legally allowed limit for the specified vehicle, which meant that for the models of this thesis' to give results based on legal driving they had to be filtered. In order to visualize the data and try to use it in a productive way, MATLAB's built in distributionFitter was used to first visualize the data and then use its tools to get cargo weight distributions for all three vehicle types.

The bin rules associated with the visualization were in all cases set to 50, regardless of the amount of data points. This was done in order to get a distribution more comparable to each other from the data. The cargo weights in the filtered data were spread out according to the visualization in Figure 8. The difference in thickness in Figure 8 between the different vehicles is due to the amount of data for each of them, where there were 155 rows of data for 98 ton, 51 rows for 74 ton and 43 for 64 ton. The 98 ton truck had the most data which is why its lines are the thickest. For the 98 ton truck one can observe an empty range between 56 ton and 61 ton in Figure 8 which is due to the truck transporting either raw wood chips or recycled wood chips which both have very different densities.

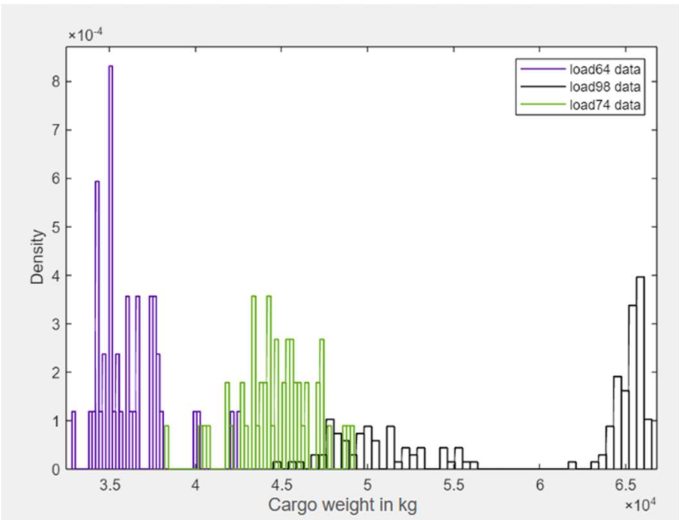


Figure 8. Visualization of the data in DistributionFitter with bin rule 50. Cargo weight in kg on the x axis, and probability density on the y axis for all vehicles in ETTdemo flis [6].

3.3.3 Formulas and equations used

The equations and formulas used in this study mostly derived from the ETTdemo flis study [6]. Other sources come from Stora Enso and LBC frakt that provided distances for planned routes for heavy electric vehicles in Karlstad.

The aim of the model was to compare 98,74 and 64 ton trucks to each other and determine their individual efficiency in terms of kr (SEK) per cargo transported and fuel efficiency per ton transported cargo. In order to simulate how much wood chips that would be transported in a given time frame, depending on the data both normal distributions and non-parametric distributions were used. Normal distributions were applied to both the 74 and 64 ton trucks due minimize the risk of overfitting the distribution to the data. The non-parametric distribution were used for the 98 ton truck due to the data distribution being bimodal [28, p. 35-64] which can also be seen in Figure 8 where there are no recorded loads between approximately 55-62 tons for the 98 ton truck. The normal distribution for 64 ton had a mean value of 36204 kg and a standard deviation of 2071. The normal distribution for 74 ton had a mean value of 44671 kg and a standard deviation of 2229. The non-parametric distribution uses a kernel distribution with a kernel density estimator that uses a formula $\hat{f}_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right)$ [29] where h is the bandwidth, which in this case was 865, x are samples, n the sample size and K is the kernel smoothing function. Figure 9, 10 and 11 are visualizations of what the distributions looked like.

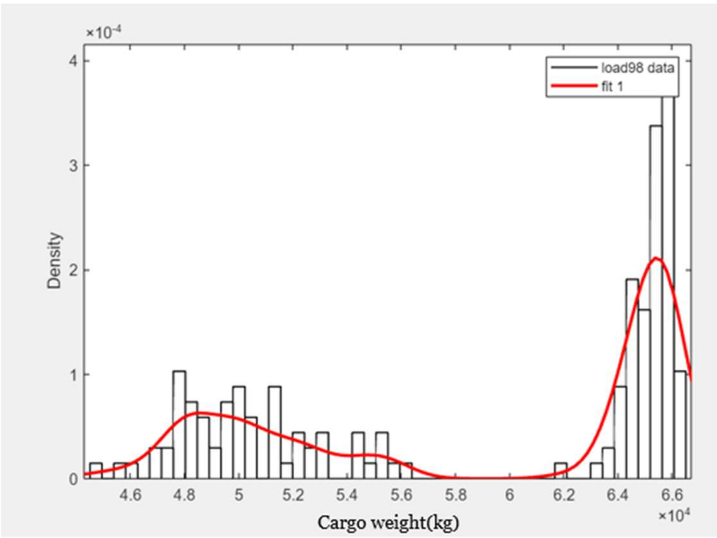


Figure 9. Fitted distribution for 98 tons and a bandwidth of 865 for the fit. Cargo weight in kg on the x axis, and probability density on the y axis.

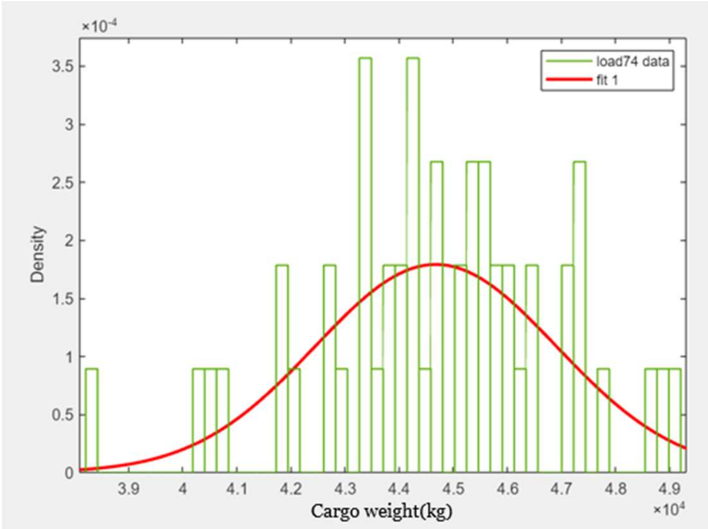


Figure 10. Fitted normal distribution for 74 tons. Cargo weight in kg on the x axis, and probability density on the y axis.

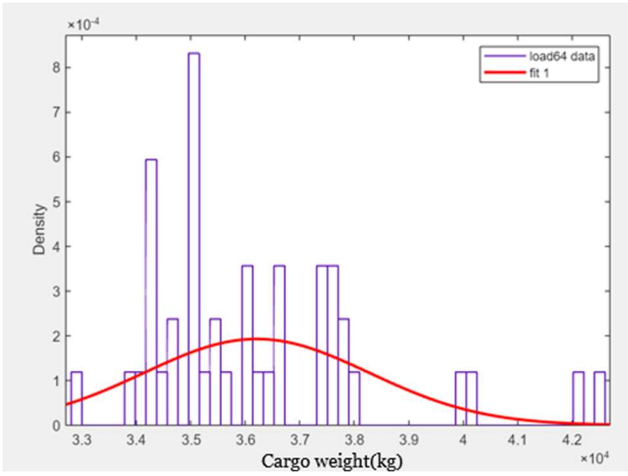


Figure 11. Fitted normal distribution for 64 tons. Cargo weight in kg on the x axis, and probability density on the y axis.

The data that existed for the vehicles fuel consumption was only given as their consumption with no cargo and with full cargo. In order to get a more accurate fuel consumption for all generated weights, a regression model for fuel consumption as a function of gross weight was created. Their respective differences between what kind of road they drove on was also considered for the fuel consumptions. Data for consumption on both highway and urban road was used. Their respective consumption with no cargo and full cargo was for 98 ton: 3,9-8,5 l/10km for highways and 7,8-11,1 l/10km for urban roads, for 74 tons: 3,9-6,1 l/10km for highways and 5,4-11,7 l/10km for urban roads, for 64 tons: 3,7-5,6 l/10km for highways and 5,3-8,9 l/10km for urban roads. With these numbers as basis for consumption, the regression model was adapted between the points. Due to available data as well as an extra data point from ETTdemo flis [6] that gave an indication of how linear the consumption was, a linear fit was used.

One could have used a non-linear fit but during discussion with supervisors and considering both acceleration, rolling resistance and the extra data point, a linear approach was deemed adequate. The plots in Figure 12,13 and 14 show what was sent as indata into the simulation model where the generated weights from the distributions was sent into the linear regression model and the weights got their consumption assigned to them from the model. The indata represent the three vehicle types with cargo weights according to the regression model. For the variation in fuel consumption, it can be motivated to add it due to previous results on the variability of fuel consumption. Based on the results from [9] it was decided to add a normal distribution as variability to the fuel consumption regression model with a standard deviation of 0,14 for 64 ton and 0,15 for 74 and 98 ton. The results from [9] gave different standard deviations than implemented here, but by taking a mean from their results and adjusting it to make the variability similar in this study to what was observed in theirs, one could argue that such an assumption for variability would be more justified than choosing a standard deviation at completely random. In Figure 12,13 and 14 one can also observe the cut off in cargo weight for the different vehicles to the right.

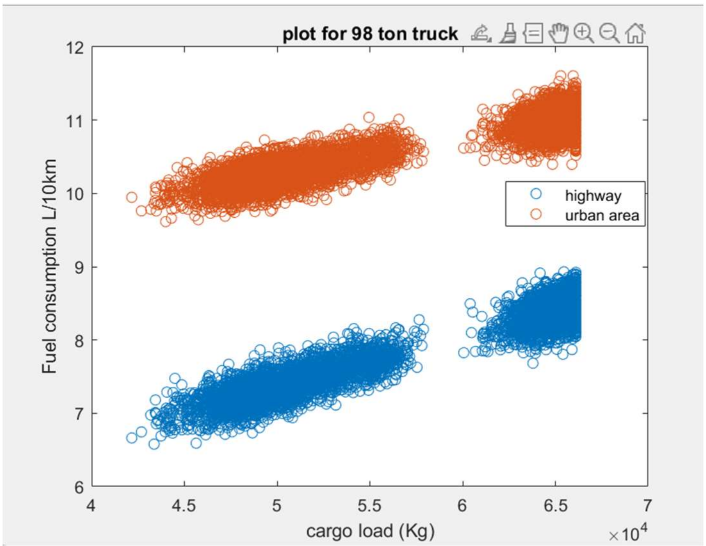


Figure 12. Relation between cargo weight and fuel consumption for 98 ton trucks.

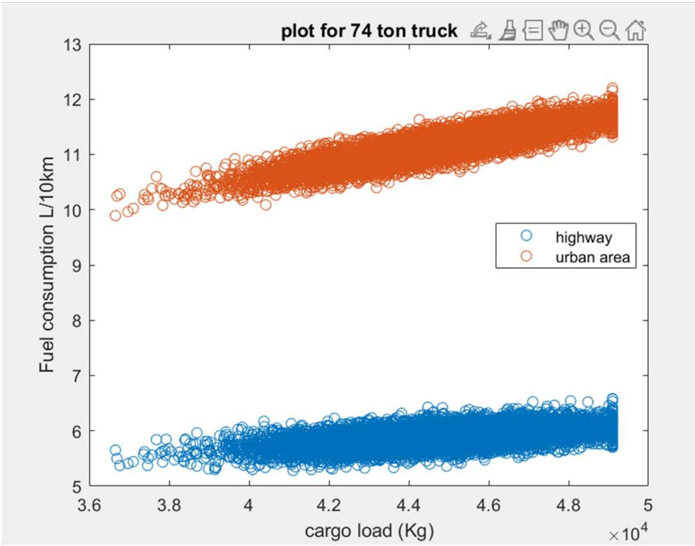


Figure 13. Relation between cargo weight and fuel consumption for 74 ton trucks

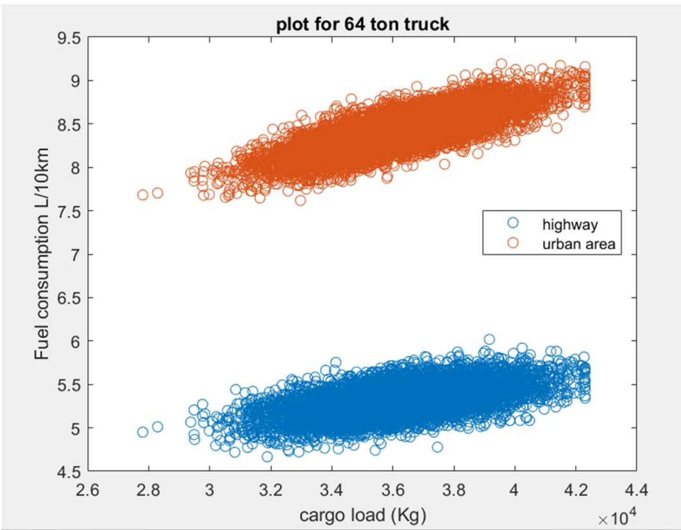


Figure 14. Relation between cargo weight and fuel consumption for 64 ton trucks

In order to get a more complete picture of the entire system some costs also had to be incorporated into the simulations. Table 9 does not have the exact same costs as the original ETTdemo flis study [6]. This is because some of the costs have been calculated differently. Good examples of this are the salary which for ETTdemo flis [6] was different between 64 and 74/98 tons because of the number of work days which in this study is set to the same amount for all vehicles, 310 days. The cost of fuel was in ETTdemo flis [6] calculated and presented as kr/10km, but in this study the cost of fuel was very varied and therefore better represented as a fixed fuel with kr/liter instead. This was also due to the fact that the trucks used fuel at the different unloading and loading zones which did not include driving distances within these zones.

Table 9. Different costs for 64,74 and 98 ton trucks, from ETTdemo flis [6].

Costs	64 ton truck	74 ton truck	98 ton truck
Investment, kr	3 500 000	3 915 000	5 315 000
Workdays a year	310	310	310
Fixed depreciation, kr / year	358 400	427 200	505 600
Interest, kr/year	178 000	197 920	265 120
Taxes, insurance and other, kr / year	173 500	173 500	173 500
Moving depreciation, kr /10km	8,3	9,3	12,8
Tires, kr / 10km	12,7	15,5	17,8
Fuel, kr/liter*	25	25	25
Service and repair, kr / 10km	19,3	19,3	24,1
Salary, kr / hour	258	258	258

*The price of diesel is set to 25 kr/l in accordance with the calculation model [24].

In ETTdemo flis [6], one of the key performance indexes most relevant to that study was kr/ton when evaluating a given trip. That unit was relevant because of the fixed distance the different vehicles drove. One unit used was also

$$\frac{ml}{ton*km} = fuel\ efficiency \tag{1}$$

Which is good for comparing with regard to distance. This is because the income for transports is partially based on driven distance and not just how many tons that have been delivered. It also depends on where the cargo is coming from. For calculating the cost of a single transport, costs for the entire year were divided by the number of transports of the simulated year. All costs were added together where the fuel spent and other costs related to transport distance were calculated from the model and put into a vector to be easily accessed in the model. Costs were then divided by the cargo weight multiplied with the transport distance to give a fair relative description of the efficiency of the specific transport. In a more easily readable form the equations used for each transport was

$$Total\ cost = Taxes + Insurance + Other + Fixed\ Depreciation$$
$$+ Interest(98,74,64) + Fuel(liter) * Fuel\ price + Tires +$$
$$Service(98,74,64) + Salary * Time \tag{2}$$

and

$$\frac{Total\ cost}{ton*km} = price\ efficiency \tag{3}$$

3.3.4 Terminal driving, ETTdemo-flis

From the literature as well as conducted interviews, terminal driving was chosen as a first avenue of modeling due to its simple resource need flow. The interviewed group, the ETT-group, all had similar opinions regarding where it would be most suitable to implement these heavy trucks first and foremost, in terminal driving. By modeling terminal driving from an already existing case it also became apparent that it might be reasonable to use the available data from that study on a more complex case.

3.3.5 LBC frakt/Stora Enso in Karlstad

In the application for LBC frakt/Stora Enso, ETTdemo flis [6] is mentioned as a source to build upon and try to mimic in some ways. Hence this thesis has taken the same cargo weight data from ETTdemo flis [6] and applied it to the LBC frakt/Stora Enso case as well. In the LBC frakt/Stora Enso the plan is to use heavy electric vehicles. ETTdemo flis [6] used diesel as fuel when calculating costs and evaluating the effectiveness. Even with that as background it is relevant to try and predict the relative effectiveness of the different vehicles in a more complex case like LBC frakt/Stora Enso in order to be able to make broader predictions of their respective performances. The chosen routes are shown in Figure 15 and had a priority list in this order: Stora Enso Gruvön-> Stora Enso Skoghall, Vänerhamn-> Stora Enso Skoghall, Stora Enso Gruvön-> Karlstad Energi Heden verket, Moelven Valåsen-> Stora Enso Skoghall and Moelven Otterbäcken-> Stora Enso Skoghall.

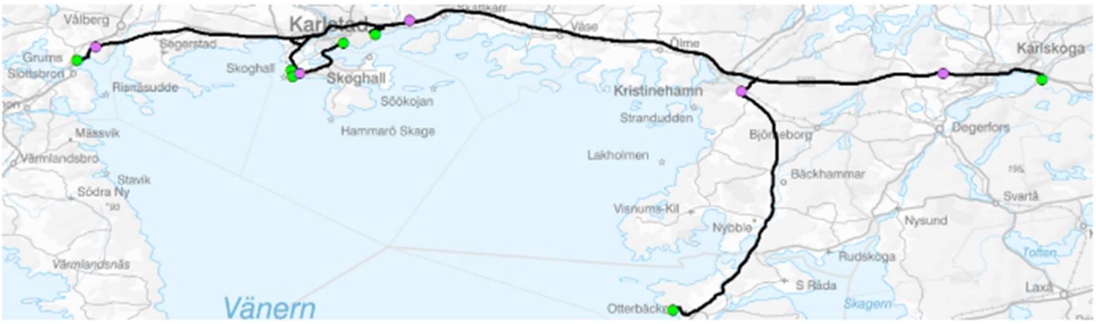


Figure 15. Map over road network. The main government owned roads relevant are the E18 and Rv 26. The green dots are the industries and the purple ones are electric loading places.

The same set of conditions that were used in the terminal driving were set for LBC frakt/ Stora Enso, which entailed time cut offs, empty supplies and truck lifespan. In LBC frakt/Stora Enso there was two off loading places which can be seen in the above priority list. The LBC frakt/Stora Enso case had the same MATLAB code as the terminal driving but expanded. The big difference was a number, chosen randomly from a uniform distribution between one to five to represent the five different routes. A uniform distribution of chosen routes was chosen because of the unknown consequences the routes driven might have on the amount of commodity transported and the amount of kr/ton. By having a uniformly chosen route all different routes could affect the results equally.

3.3.6 Model limitations

The truck has not been modeled to need to fuel up or be stored in a garage at a different locations than the industry during nights due to lack of data of those events as well as their little effect on the relative difference between the vehicles. When one truck has driven its last transport for a day it just stays the night at the off loading place. The model has only taken into account the number of trips per day and if those trips exceed the allowed working hours for a given day. The number of days a year has also been set to what they used in ETTdemo flis [6], except for the 64 ton truck where in this study the same number of days for all vehicles was used, 310 days.

The fuel consumption depends on road attributes such as elevation and other factors. Factors and numbers for road conditions, load and unloading times that are specific to other cases than ETTdemo flis [6] have not been taken into account due to available data. Different types of wear have not been implemented either.

In this study, economic factors have been addressed through a full-cost analysis of the haulers' operational costs. How haulage companies negotiate and make profits has not been considered, only in terms of money saved.

4. Results

The results are split into qualitative data from the literature study and the interviews where the qualitative data aims to further concretize barriers and what they mean. Then results from the simulations are presented. The results from the simulations aim to provide a good basis for what kind of reduction in costs that might be achievable and what those reductions might mean in terms of transported wood chips and reduced emissions.

4.1 Interviews

From the interviews a few important factors were mentioned as imperative for HCTs to be effective at even bigger sizes. Logistical flows need to be consistent and not too varied in regards to how much or little commodities need to be transported and where, in order to make sure the truck has enough cargo each time to make up for its increased operating cost. What this means is that scenarios with trucks that have a very varied schedule and a lot of variations in where to drive and pick up goods, is probably a bad case for implementing 90+ ton trucks. With more stationary flows and a constant need for transports, logistics does not hamper the HCTs utilization rate and its load fill rate. Another important factor is the road infrastructure and how that relates to the HCTs. 90+ ton trucks will not be implemented if they do more damage to the roads, but this has been looked at and the big impact lies in the axle load which means that adding more axles as weight goes up will make the HCTs not much different in terms of road wear to the more traditional vehicles. The availability and limits of the BK4 road network has also been touched upon and shown to be a big barrier in the literature. Along with the availability of the road network, bridges were also mentioned as a stopping block if not rated for HCTs since it would hinder transportations or force the HCTs to take a detour.

The interviewed experts expressed some of their perceived important factors needed for an electrification of the system to be successful. The most important of these was the fact that a more clear incentive is needed for the haulage companies to invest in those technologies. Either through increased costs for diesel usage or by making it cheaper with electric trucks as well as investing in the new infrastructure needed for them.

In terms of potential, it was expressed that not more than around 10% of the total amount of trucks in Sweden would be 90+ tons due to the needs that exist.

4.2 Terminal driving

4.2.1 Economic analysis and CO2 emissions

The terminal driving scenario is explained in detail in ETTdemo flis [6]. In order to get a good representation of the different vehicles' efficiency compared to each other, each driven transport was calculated and plotted according to Equations (2) and (3) which can then be seen in Figure 16. In Figure 16 each point represents one route driven. For each cargo weight there is either one, two or three different colored points representing the vehicle transporting the cargo. For each color there is also some variation in (3) due to the driven transports per year since many costs were divided among all the driven transports. It can also be observed for all results that in certain ranges the number of points (driven transports) are much more densely populated than other ranges. In order to talk about the potential for the 98 ton truck the mean of kr/ton and of kr/10km were calculated over a simulation period of ten years which can be seen in Table 10.

The distribution of Equation (1) was used in the same way as for Equation (3) to give a good representation between the vehicles and as can be seen in Figure 17 there is a relatively smaller difference between the 64 and 74 ton truck compared to the relative difference in Equation (3) which can be seen in in Figure 16.

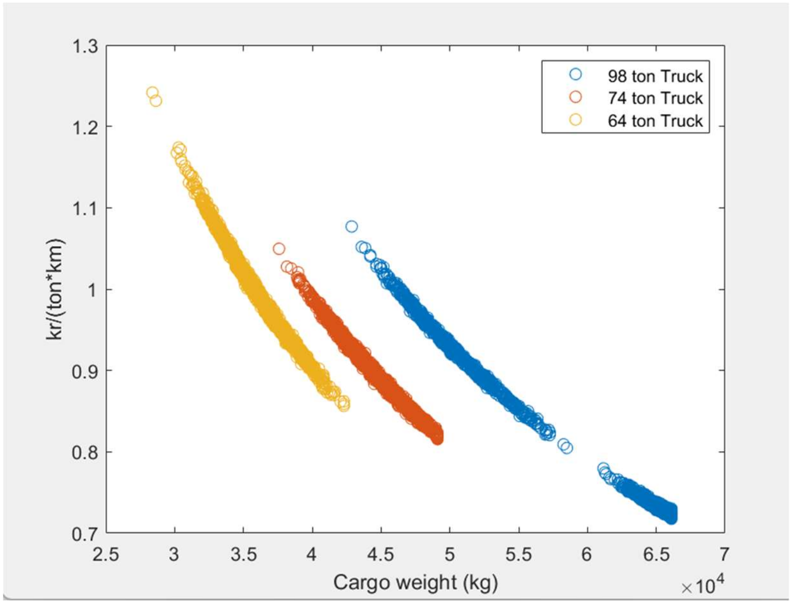


*Figure 16. Simulation of ten years of driving. Spread of kr/(ton*km) for the different vehicles when going between two points.*

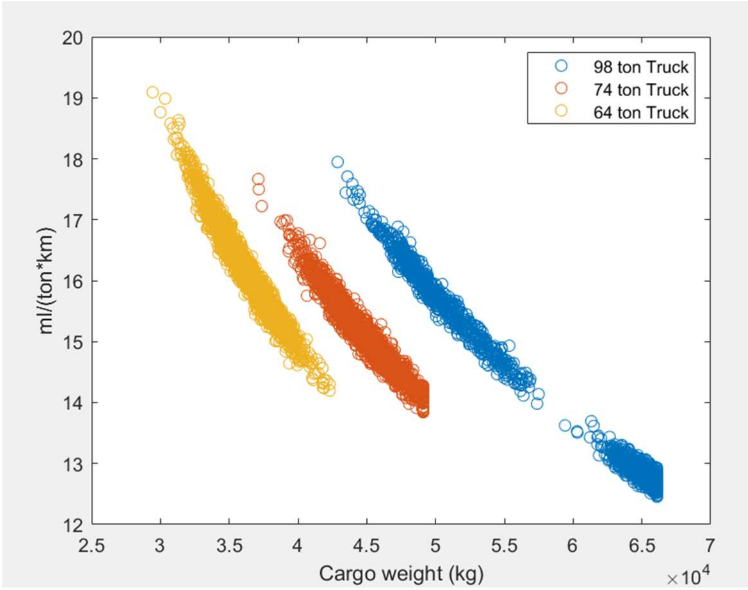


*Figure 17. Simulation of ten years of driving. Spread of ml/ton*km for the different vehicle when going between two points.*

Table 10. Mean values for cost calculations, simulated over ten years.

Costs	64 ton truck	74 ton truck	98 ton truck
Kr/ton	41,66	37,49	33,87
Kr/10km	358	398	475
l/ton	0,68	0,64	0,58
l/10km	5,85	6,76	8,16
10km/year	7799	7850	7800
Delivered ton/year	67 000	83 500	109 400

4.2.2 Potential savings by using heavier trucks

With the results from Table 10 one can easily make some predictions of the amount of saved money by using the higher gross weight trucks. Worth to have in mind with these results is that all three vehicles drove approximately the same distance over time which is then reflected in the amount of km driven per year. If one assumes a need of 100 000 tons/ year in approximation to what has been described in ETTdemo flis [6], then there is a potential in savings based on the kr/ton from the results. It would cost the 64 ton truck 4 166 000 kr, the 74 ton truck 3 749 000 kr and the 98 ton truck 3 387 000 kr to deliver 100 000 tons of goods. With subtraction between the 98 ton truck and the 64 ton truck the potential in savings comes out to 779 000 kr per year and truck. Doing the same thing for the fuel consumption gives a reduction of 10 000 liters of fuel.

4.2.3 Diesel price effects and economic margin on the 98 ton trucks

From these results it also becomes relevant to find out what the minimum conditions in terms of average cargo would be for the 98 ton truck and still be more efficient than the other two vehicles. By reducing the cargo load in percentage it was found that the limit for when the 74 ton truck and the 98 ton truck were similar in efficiency was at 10% less cargo on average . In Figure 18 one can see that the highest loads of the 98 ton trucks are still more efficient but that the lower loads reduce the efficiency. The mean values for the 98 ton were the same as the 74 ton truck at 10%.

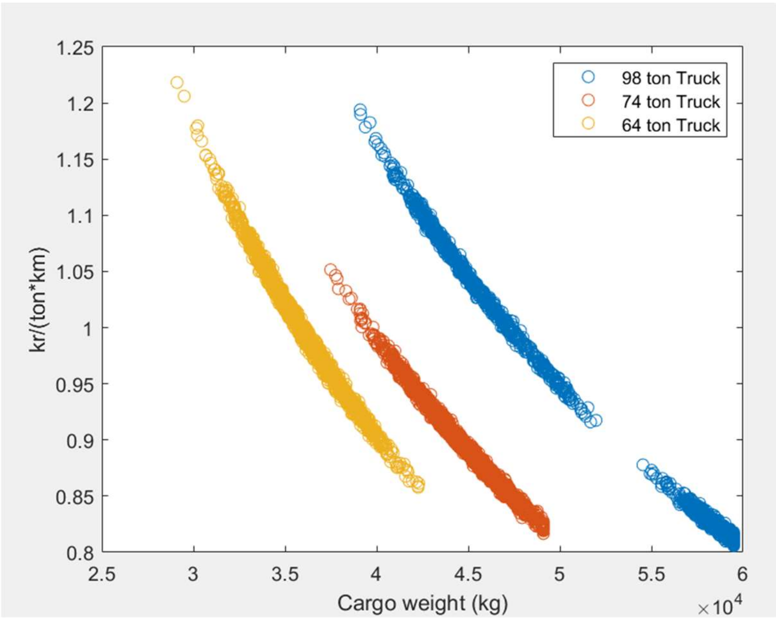


*Figure 18. Simulation of ten years of driving. Spread of kr/ton*km for the different vehicle when going between two points, with a reduced cargo load for 98 tons.*

In order to understand how important the fuel cost is on the system, different prices were used to see the differences the price of fuel might have. “Elpriset.se” [28] which is not a reputable source but still gives estimates on the prices from 2017-2024, was used. Given their estimates on what the price of diesel has been, those prices were used in the simulation instead of the 25 kr previously stated. The vehicles’ relative differences was not affected much by changing the price of diesel. When the price was 14 kr / liter the differences in mean values were 27,47 kr/ton for 98 ton, 30,53 kr/ton for 74 and 34,24 kr/ton for 64 ton. When the price was 18 kr / liter the difference was 29,68 kr/ton for 98 ton, 33,09 kr/ton for 74 ton and 36,88 kr/ton for 64 ton.

4.3 Stora Enso and LBC frakt

4.3.1 Economic analysis

The economical analysis for the Stora Enso and LBC frakt scenario is the exact same as for the terminal driving scenario. For each cargo weight there is either one, two or three different colored points representing the vehicle transporting the cargo. For each color there is also some variation in (3) due to mostly the number of driven transports per year since many costs were divided among all the driven transports. The vehicles' performance relative to each other is displayed in Figure 19 and shows that the 98 ton truck yields the lowest (3) when it is close to or fully loaded. In the plot there appears to be only four groups of lines for the simulation in Figure 19 even though the routes driven were five. This is because several routes were very similar in distance and therefore are more closely grouped together as can be seen in the more dense lines at the bottom of the plot in Figure 19.

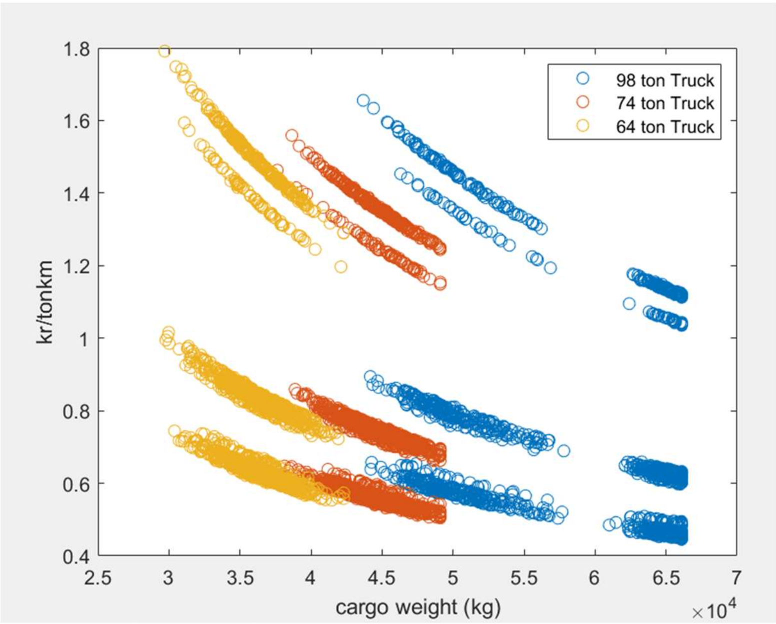


*Figure 19. Simulation of ten years of driving. Spread of kr/(ton*km) for the different vehicles when driving five different routes.*

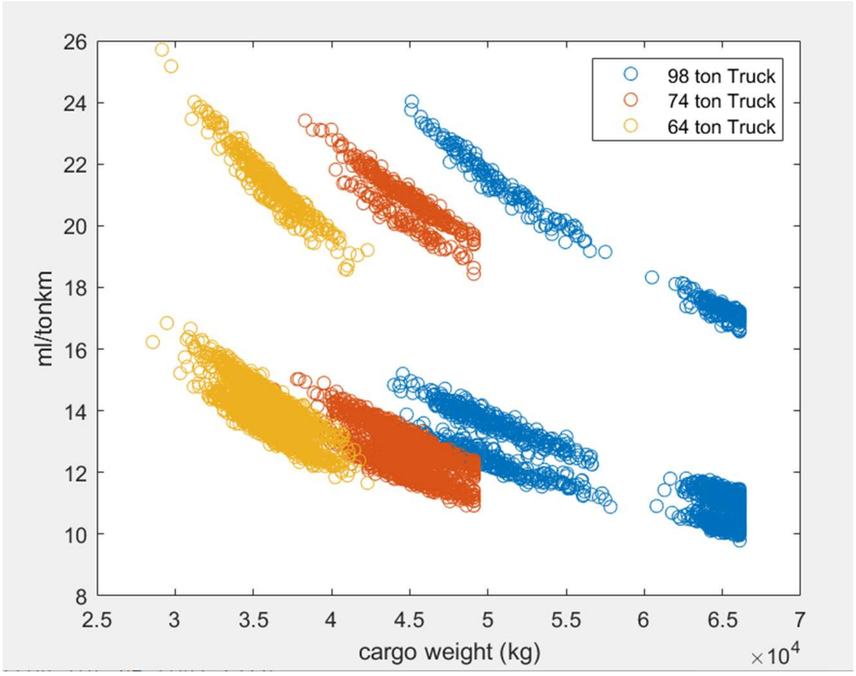


*Figure 20. Simulation of ten years of driving. Spread of ml/ton*km for the different vehicles when driving five different routes.*

The same phenomenon that was observed in Figure 19 was also present when calculating the fuels' impact. Since a normal distribution was added to the fuel consumption it made the variation in consumption when looking at Equation (1) even bigger than in Equation (3) which is why in Figure 20 it seems to be only three driven routes when in fact those results are from the same simulation as in Figure 19.

Table 11. Mean values for cost calculations, simulated over five years.

Costs	64 ton truck	74 ton truck	98 ton truck
Kr/ton	72,69	63,89	58,04
Kr/10km	261	286	342
l/ton	1,41	1,27	1,17
l/10km	5,06	5,69	6,88
km/year	17 600	17 700	16 700
Delivered ton/year	62 900	78 000	99 400

4.3.2 Potential savings by using heavier trucks

With the results from Table 11 one can draw the same conclusions as in the terminal driving case in the Stora Enso case.

As with terminal driving the assumed need in order to make predictions in the saved amount of money is the need for 100 000 tons/ year.

It would cost the 64 ton truck 7 269 000 kr, the 74 ton truck 6 389 000 kr and the 98 ton truck 5 804 000 kr to deliver 100 000 tons of goods. Subtracting between the 98 ton truck and the 64 ton truck the potential in savings comes out to 1 465 000 kr per year and truck. For the fuel reduction the amount of saved fuel is 24 000 liters of fuel.

4.3.3 Diesel price effects and economic margin on 98 ton trucks

The same trends as in terminal driving were obtained in the LBC frakt/Stora Enso case. The limit for greater efficiency was found at 10%. The results from the simulation are shown in Figure 21. The mean values for the 98 ton were the same as the 74 ton truck at that percentage.

Doing the same thing for the price of diesel as in terminal driving one retrieves results as follows. When the price was 14 kr / liter the 98 ton truck had 45,54 kr/ton, the 74 ton truck had 50,1 kr/ton and the 64 ton truck had 56,98 kr/ton. When the price was set to 18 kr / liter the 98 ton truck had 50,16 kr/ton, the 74 ton truck had 55,23 kr/ton and the 64 ton truck had 62,38 kr/ton. The price differences are higher in this case, since the routes in the LBC frakt/ Stora Enso case were much longer than in the terminal driving.

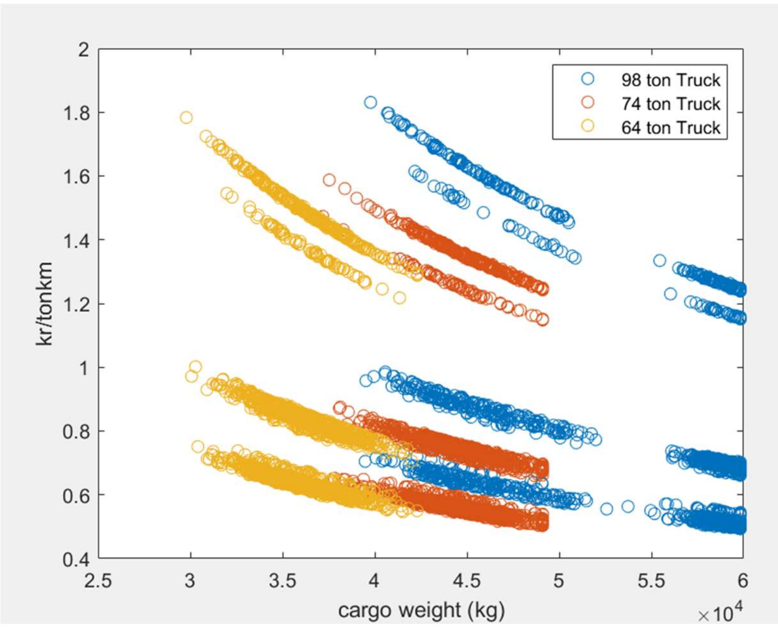


*Figure 21. Simulation of ten years of driving. Spread of kr/ton*km for the different vehicle when just going between two points, with a reduced cargo load for 98 tons.*

5. Discussion

5.1 Method

The thesis has used three methods in order to answer the research questions. These methods have been used with the intentions mentioned in Table 8. Even though they have covered a lot of topics, there are things that might have been missed using them.

During the interviews a lot of relevant material was brought up and later used in the thesis. Looking at the number of interviews, one could make the argument that the amount of diversified input was limited. If more interviews would have been done one might have acquired more perspectives on the system as a whole.

Even though the Swedish forest industry is very different from countries like Canada, Australia and the US it could have been helpful to analyze more studies from abroad and incorporate those findings into a broader case for the Swedish forest industry.

The results from the simulation did show a reduction in cost and a reduction in environmental impact through reduced fuel consumption. For the cost reduction one aspect missed through the simulation is how longer distances affect the cost through payment. Since its more expensive to drive longer distances than shorter distances the haulage companies receive payment in accordance with the driven distance as well as the delivered product. The trucks also had lifespans according to driven km which would then be reached sooner the more km driven. Replacing a truck and buying a new one was not considered.

5.2 Differences between results

In the original ETTdemo flis [6] it was found that the 74 ton truck performed worse than the 64 ton one. This result did not appear when driving the same route during the simulations in this study. This could be due to many factors where one of the main ones probably is the data handling. From the original data a lot of it was filtered out due to weight classifications and truck configurations in order to make sure the generated distributions never exceeded the legally allowed limit. In ETTdemo flis [6, p. 27] the total amount of delivered wood chips in ton/year was 89 037 for 64 ton ,97 780 for 74 ton 119 889 for 98 ton trucks which is different from the amount of goods delivered in this study. This however is no surprise since the conditions for the different trucks during the simulations were the same in terms of the number of transports being done in a year. It was assumed that the 64 ton truck also had 310 work days a year to make a fairer comparison between the vehicles, which was different from the days driven in ETTdemo flis [6], which had 270 days for the 64 ton truck.

5.3 Simplifications

Some simplifications were made during the simulations in order for it to make them feasible given the scope of this thesis. Some of the simplifications were:

- Linear fuel consumption to weight as opposed to a more stochastic fit.
- The simulated trucks only traveled between off loading and loading places, never to any other place like a mechanic even though costs for those services were considered. Since the driven days also were 310 days one can assume that service took place during one of the days not driven during the year.
- Only two types of road were considered where these roads yielded different fuel consumption for the different weights of the trucks. For future studies it might be a good idea to categorize different roads in more ways than two in order to capture more variations in fuel consumption related to speed and road attributes.
- The amount of goods delivered was only determined by the specified amount of rounds per day which was set to a maximum of nine if the time allowed it. In other words, the amount of goods needed at the industry was not taken into account.
- No breaks were implemented in the simulations. Breaks and shift changes were not implemented in the simulations. These factors will however be very relevant when the system changes and becomes more electrified.
- The amount of highway vs urban roads was set arbitrarily. These numbers for the Stora Enso case were set according to what was observed in google maps.
- Due to road maneuverability and the difference in driver experience between normal trucks and the heaviest HCTs, the driver's driving style depending on road, type of truck and season was not considered [7] [4].

5.4 Data Limitations

The data used contained gross weights as well as truck weights and what times the transport departed. Information on driving speeds, costs and what kind of road driven on was also available and considered when setting parameters.

More complex data such as need structures were not used, which might give a difference in comparing the different vehicles and their utilization. This was a trade off between keeping the need for a certain amount of goods constant for all vehicles and letting them drive approximately the same distance over time.

5.5 Previous studies

5.5.1 Relevant factors

In the literature study many different factors were looked at and evaluated to find the most important barriers to deal with in order to use heavier HCTs. From ETTdemo flis [6] the load fill rate was determined to be a requirement and a barrier for HCTs since the limiting volume available on the trucks might impede how much mass is transported and therefore reduce the cost reduction made possible by the bigger trucks. That factor was heavily dependent on what volume the truck configuration made possible, since the same restriction on volume was not found in either 64 ton or 98 ton trucks.

Electrification from the literature was determined to be very important for the future of the transport system in Sweden. The conclusions from the studies analyzed show a need to incentivize electrification, as well as to what extent changes in the logistics part of the system would be necessary. These changes contained infrastructure for charging the trucks and a new contract model between haulage companies and the industries. Even though this study did not touch upon electrification it is worth acknowledging the limitations that might arise in the Stora Enso case if the charging infrastructure is not both flexible and rigid to handle the load that might be put on it.

The current road infrastructure with the highest classification, BK4, is in need of further expansion in order to simplify the next step, the use and need for 90+ ton trucks. It is partly a matter of classification as many roads probably could handle the stress of HCTs, but are not classified as such as of current. As has been demonstrated, the road network does not always make needed transports possible due to the limitations in allowed vehicle weight. An important aspect of the roads infrastructure is its bridges too. Bridges can easily become a stopping block for transports, since some might not be classified for certain weights. Some bridges might be able to be reclassified for higher weights [29].

As was seen in Transportarbetaren [17] there is a need for more new drivers in the transportation sector in Sweden. But not only does Figure 4 show a reduction in needed drivers, it also means there will be less truck space in meters on the road when implementing more HCTs. This fact is important but more of an extra bonus if other factors such as economic profit or CO2 emissions show a positive trend from data.

5.5.2 Other factors

Factors present but without much influences were driver behavior which was briefly discussed in ETTdemo flis [6] and in “Performance assessment of high capacity trucks: Understanding truck selection and deployment economics” [9]. Both these expressed the slight difference the drivers experienced between the vehicles in terms of maneuverability, starting and stopping. The only experience expressed that was worse in the heavier 74 and 90+ ton trucks was starting with no cargo in bad weather conditions due to the low axle load on the drive wheels when a high mass starts moving[6]. This is something to keep in mind if one implements HCTs to a higher extent than has been previously done.

Another factor determined to be very limited in its effect on the system was different types of wear. Especially important was the finding that the most important factor for road wear was the axle load, which for 98 ton trucks is no greater than what is already legally allowed for smaller trucks.

There exists a potential in the form of aerodynamic improvements for trucks on the road. These conclusions however are not unique for HCTs and are therefore most relevant as potential for the whole system rather than a potential in HCT. A possible subject for further research in this field is whether HCTs gain even more effectiveness from the aerodynamic improvements compared to other trucks.

5.6 Other cases not studied

During this study other cases than those presented have been encountered. The most notable one is kappa/Haraholmen [30] where Volvo has measured the fuel consumption of HCTs. Fuel consumption, axle load and time were all measured. The case and its relevance was first encountered during talks with Lennart Cider, where Volvo and Vinnova have continued to do trials. Due to lack of comparative data for other vehicle configurations this case was not chosen for simulations.

6. Conclusions

During this thesis a literature study has been done to highlight what and how much research that has been done. Some interviews with experts were done to give a direction and delimit what kind of work that this thesis could treat. Lastly a simulation study with two cases was done. One case was more complex in terms of routes and places to transport to.

6.1 Answering the Research Questions

The potential observed in this study points to a positive trend in both money saving and fuel reduction, when driving wood chips in a system with more pickup places than has already been studied. The results have helped to make the case that even heavier HCTs than today has the potential to help improving the transportation system further by increasing effectiveness and lowering the number of drivers needed. It has also been demonstrated how one could make these predictions: partly by implementing an event based simulation model and partly by the already established calculation models.

In order for the transportation system to have more HCTs and utilizing them properly an adequate road infrastructure is needed, as well as bridge improvement in some places. For electrification, which is on its way, new models for contracts and route optimizations are needed to fit the new capacities of the trucks.

For 90+ ton trucks to be more profitable and effective they need to have a high fill rate as well as high utilization since they are more expensive to drive.

The most suitable cases for 90+ ton trucks to drive are cases that have fixed biomass flows from different routes or just single routes like terminal to terminal. They are not suitable in cases that have a very varied biomass flow with more variable pick up and unloading places that get served.

Increasing allowed weight and using trucks that have a gross weight over 90+ tons is a complex question where each case should be studied in detail before implementation. Although a lot more research is needed in different fields, 90+ ton has the potential to help improve the transportation sector in Sweden and ease both the economic burden and the need of truck drivers.

6.2 Practical implications for the future

For the future when implementing 90+ ton trucks, they need to be used in cases that have a good margin of supply needs and a well established road network to utilize the trucks' potential. The companies that will operate these vehicles will need to make sure the volume available is sufficient for the weight they aim to carry. What kind of implementation that investors choose in the future is partly based on return of investment which in this case would mean that 90+ ton trucks probably will be more used in the future if the system as a whole can become more adapted to it, which it seems.

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Appendix A

Questions in Swedish:
1.Projektet går ut på att undersöka potentialen av 90+ tons lastbilar. Inom vilka kontexter ser du dem som mest användbara om?
2.Vilka är farorna, riskerna eller nackdelarna i ditt tycke som kan komma ifall man implementerar dessa tyngre bilar, störst hinder?
3.Vilka KPI:er är viktigast för dig för att kunna eller vilja att dessa fordon implementeras inom industrin, vad ska man titta på och undersöka/ prioritera?
4.Inom ramen för min examensarbete, Vad bör man undvika att gräva sig för djupt inom? Jag tänker, exempelvis med bränsleeffektivisering av bensinbilar.
5.Behovsmässigt, hur bör man se på en blandning i vägnätet av dessa bilar, Vad skulle i ditt tycke kunna vara skäl till att blanda olika kombinationer av lastbilsstorlek?
6.Hur tror du elektrifiering kommer ändra scenariot med 90+ ton fordon?
7.Hur kan flödena se ut där dessa fordon kan komma att använas. Är dessa flöden känsliga, och i så fall, skulle en implementering av ännu tyngre fordon kunna göra dem ännu känsligare?

Questions in English:
1. The project aims to investigate the potential of 90+ ton trucks. In what contexts do you see them as most useful, if at all?
2. What do you consider the dangers, risks, or drawbacks that could arise from implementing these heavier vehicles, the biggest obstacles?
3. What Key Performance Indicators (KPIs) are most important to you in order to be able or willing to implement these vehicles within the industry, what should be looked at and investigated/prioritized?
4. In the scope of my thesis, what should one avoid delving too deeply into? For example, with fuel efficiency in gasoline cars.
5. In terms of needs, how should one view a mix of these vehicles on the road network? In your opinion, what could be the reason for blending different combinations of truck sizes?
6. How do you think electrification will change the scenario with 90+ ton vehicles?
7. What could the flows look like where these vehicles might be used? Are these flows sensitive, and if so, could implementing even heavier vehicles make them even more sensitive?