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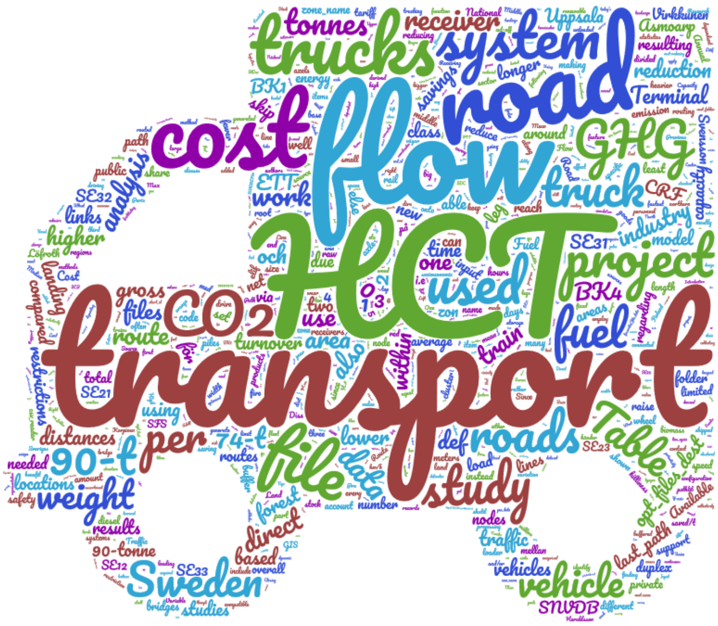
Swedish University of Agricultural Sciences

Department of Forest Biomaterials and Technology

A method of finding HCT roundwood corridors for reduction of GHG emissions and hauling costs in Sweden

En metod för att finna HCT-korridorer som besparar växthusgasutsläpp och transportkostnader i Sverige

Christian Höök



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A method of finding HCT roundwood corridors för reduction of GHG emissions and fuel costs in Sweden

En metod för att finna HCT-korridorer som besparar växthusgasutsläpp och bränslekostnader

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Abstract

In Sweden, 71.6 million tonnes(t) of forest biomass were during 2016 transported by truck, corresponding to approximately 15 % of all national goods truck transport. To reduce the environmental impact of forest product transports and meet Swedish climate goals, the use of 90-t high capacity transport (HCT) trucks on well-chosen routes has been identified as one potential measure to reduce impact.

The objective was to develop a method of finding the geographical occurrence of potential roundwood HCT corridors for 90-t trucks, as well as estimating their environmental and economic potentials in comparison to the conventional 74-t truck transport system for Swedish conditions. The study used data from actual roundwood transports during 2016 along with a digitalization of the Swedish road network (SNVDB) for corridor identification.

Results showed there were 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 of CO_2 and €3.1 M in fuel costs.

Keywords: High Capacity Transport, fuel consumption

Sammanfattning

I Sverige transporterades 71,6 miljoner (M) ton (t) skogsråvara med lastbil under 2016, motsvarande omkring 15% av all nationell lastbilstransport. För att minska klimatpåverkan och nå de svenska klimatmålen har användningen av 90-t högkapacitetstransporter (HCT) på utvalda vägar identifierats som potentiellt fördelaktig.

Syftet med studien var att utveckla en metod för identifiering av den geografiska förekomsten av potentiella HCT-korridorer för rundvirkestransport med 90-t lastbilar samt att uppskatta deras miljömässiga och ekonomiska potentialer jämfört med det konventionella 74-t lastbilstransportsystemet för svenska förhållanden. Studien använde data från faktiska rundvirkestransporter under 2016 tillsammans med den skogliga svenska vägdatabasen (SNVDB) för att identifiera korridorer.

Resultaten visade att det fanns potential att anlägga 25 HCT-korridorer med totalt 20 90-t lastbilar som kunde frakta 2,5 Mt rundvirke och därigenom spara 5500t CO2-utsläpp och €3,1 M i bränslekostnader.

Nyckelord: Högkapacitetstransporter, bränsleförbrukning

Preface

This master's thesis was initialized by Skogforsk, the Forestry Research Institute of Sweden.

I would like to thank Dan Bergström (SLU), Victor Asmoarp (Skogforsk), and Björn Edlund (SLU) for great supervision and brainstorming throughout the process of this thesis.

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Abbreviations

1 Euro = 10.22 SEK (190109)
1 L diesel = 2.81 kg CO_2
1 L diesel = €1.55 (190109)
CRF = Calibrated Route Finder (Krönt Vägval)
HCT = High Capacity Transportation
M = Million
k = thousand
l = Liter
CO_2 = Carbon Dioxide
GHG = Greenhouse Gasses
Route = A transport route between a landing and a receiver
HCT Corridor = A specific portion of a transport between a source and a sink of roundwood where all cargo is uninterruptly transported on 90-t trucks.
Leg = Part of a transport. In this study, most transports are comprised of three legs – from forest to terminal, from terminal to terminal, and from terminal to industry (total three legs).
Link = any one small link between nodes in a transport route
Terminal = End nodes in an HCT corridor, typically an area where round-wood is stored and/or reloaded onto another transport vehicle.
Cluster = Adjacent corridors with terminals closer to eachother than 20km
GIS = Geographic information system, a computer software (e.g. ArcGIS, QGIS) for spatial analysis.
Python = A high-level and general-purpose programming language.

1 Introduction

To reduce the environmental effects caused by human post-industrial activity, the world now faces the challenge of reducing greenhouse gas (GHG) emissions. The Paris agreement states that participating parties pledge to keep the global average temperature to well below 2 °C of pre-industrial levels, with an additional pursuit to limit the temperature increase to 1.5 °C (United Nations, 2016). The European Union commits to the 20/20/20-package, which compared to 2008 levels should facilitate: reduction of GHG emissions by 20%; reduction of energy use by 20%; the share of renewable energy of final energy use should amount to 20% (Swedish Energy Agency, 2018). Additionally, the share of renewable energy in the transport sector shall be at least 10%.

Swedish climate- and energy goals include that the share of renewable energy in the transport sector shall be at least 10% by 2020, net zero GHG emissions compared to 1990 by 2040, and 70% lower GHG emissions from domestic transport (excluding domestic flight) 2030 compared to 2010 (Swedish Energy Agency, 2018). National transports account for a third of Sweden's total GHG emissions, of which 94% is due to road transports (Swedish Environmental Protection Agency, 2018). In 2016, 71.6 million (M) metric tonnes (t) of forest biomass (roundwood and forest fuels) were transported by truck, corresponding to approximately 15% of all national goods truck transports (Davidsson & Asmoarp, 2019; Forest Industries, 2017).

Transport by train generally produces less GHG emissions than road transport by trucks due to higher efficiency and the fact that trains in Sweden are mostly electrically powered. The savings in emissions by using train transport is however dependent on the energy source powering the train. In Sweden, 98% of the electricity production is non-fossil based making train transport virtually fossil free assuming electrical independency (Swedenergy, 2018). With longer distance and higher transport capacity, train transport productivity is increased, raising the potential for savings in both costs and GHG emissions per unit of goods with the economy of scale.

A large flow of goods and infrastructure to support it are prerequisites for effective train transport. Single train transport is also dependent on other traffic (goods or passengers) to keep the system economically viable. It is also susceptible to interferences and is accompanied by high fixed costs (Gröndahl, 2012). Since raw materials for forest products originate from ever changing sources with different stock, flexibility beyond the capabilities of trains are needed for these transports. Trucks, on the other hand, can provide much of the flexibility needed in the forest transport sector. The extensive road infrastructure combined with a plenteous of truck haulers and their ability to transport less cargo as a minimum compared to trains makes truck transport cheap and easy to use for short transports of raw forest products. Conversely, train transport is more suitable for longer and transport intensive distances, for example between terminals.

In 2014, Swedish forestry GHG emissions from silvicultural management, harvesting, and transport to industry amounted to about 970 000 t CO2, of which the roundwood transport accounted for 43.8% (Skogforsk, 2019).

Currently (2019), roundwood transports on roads typically use a conventional vehicle set with a maximum gross weight of 64 t. With new technologies, possibilities for using larger vehicle sets carrying more roundwood are emerging (Löfroth & Svensson, 2012). These high capacity transports (HCT) have the potential to lower the fuel consumption and cost per shipped unit resulting in lowering GHG emissions while strengthening the profitability of haulers.

1.1 The ETT project

Asmoarp et al. (2018) show that HCT trucks in Swedish wood supply could potentially reduce total fuel consumption and GHG emissions by up to 12%, lower road wear and increase road safety. Two variants of HCT vehicle systems have been proposed, tested and used: ST (“bigger piles”) and ETT (“one more pile”) (Figure 1) (Löfroth & Svensson, 2012). The ST system is a vehicle combination with the same length (24 m) as a conventional vehicle and with a gross weight of 74 t. The higher weight is compensated with two more axles to reduce the ground pressure from each axle. The ST system can carry bigger and heavier piles and therefore more roundwood than the conventional 60- or 64-t vehicle combination. The ETT vehicle is 30 m long with 11 axles and a gross weight of 90 t able to carry four piles of roundwood instead of three, as for the conventional. Fuel consumption of both these HCT truck systems is increased on average by about 25% compared to the conventional 60 t system due to its higher gross weight, but by carrying more roundwood every turn, the overall consumption per net weight is reduced on average by about 21% (Svensson & Löfroth, 2012).

Figure 1. Schematic illustration of a 64-t (top), 74-t (middle), and 90-t (bottom) vehicle. Picture from von Hofsten (2019)

As HCT trucks have extra axles, the higher gross weight of the vehicle is divided onto more road contact points, reducing the axle load and lowering the road wear in comparison to a lighter conventional truck with fewer axles (Asmoarp et al., 2018). Increased road contact also means increased braking (retardation) effect, making the HCT trucks similar to a conventional truck regarding road safety. Concerning frontal collisions with cars, impact violence differs only slightly at a weight ratio above 1:10 between colliders (Sandin et al., 2014). In essence it wouldn't matter if a car collided head to head with a 64, 74 or 90-t truck, impact violence would be very similar. Furthermore, studies have shown small to no increased risk associated with overtaking longer vehicles on a 2+1 road (Fogdestam & Löfroth, 2015). Arguably, overall road safety is increased with the use of HCT trucks since transporting more roundwood each turn would mean fewer trucks on the road.

1.2 Roundwood transports in Sweden

The majority of the roundwood truck transport work in Sweden 2016 was performed in the southern half (Figure 2), which is also the part of the country housing the majority of the receivers (terminals and industries) as well as the bulk of the population. The mean roundwood transport distance was 91.1 km, with variation due to Sweden's forest industry structure with more receivers of forest products in the south and along the coast (Davidsson & Asmoarp, 2019). With a decreasing density of receivers in a north-bound gradient, mean transport distances were higher in the northern part of Sweden. Few transports originated in the northern inland part, lowering the amount of performed transport work despite the longer transport distances.

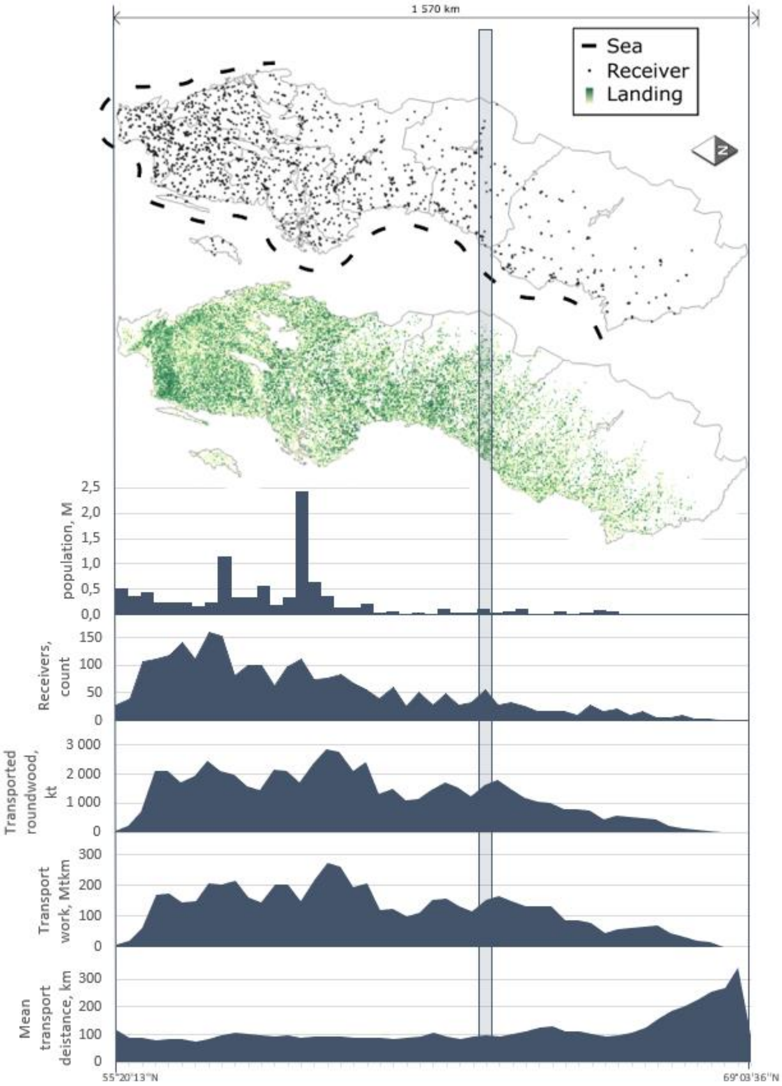


Figure 2. Geography of Sweden with cross-sections (31.4 km wide) describing population, transported roundwood, transport work, frequency of receivers and mean transport distance. The shaded elongated rectangle shows a schematic example of a cross section and its associated statistics. Source: Skogforsk (processed).

1.3 Road network

The Swedish public road network is divided into four bearing capacity classes based on maximum gross weight and axle load (SFS 1998:1276) (Table 1).

Table 1. *Definition of road classes in the Swedish public road network (SFS 1998:1276).*

Road class	Max. gross weight (t)	Max. axle load (t)
BK1	64.0	10
BK2	51.4	10
BK3	37.5	8
BK4	74.0	10

96.1% of the roundwood transport work is carried out on the public road network (Davidsson & Asmoarp, 2019). Roads with class BK1 and BK4 form a large majority of the public road network, about 82% and 12% respectively (Swedish Transport Administration, 2018). On these roads, additional restrictions may apply, such as for vehicle height in tunnels. In June 2015, the BK1 roads were updated from a maximum gross weight restriction of 60 t to 64 t. The BK 4 road class was introduced in July of 2018. A permit issued by the Swedish Transport Agency is needed to use a vehicle exceeding the road class limit (SFS 2017:1284). The permit is applied for a specific time frame, road or road network and is given to test new technology or new constructions.

Due to their restrictions in being based on gross net vehicle weight rather than axle load, bridges are often the reason many BK1 roads cannot be upgraded to BK4 (Natanaelsson & Ngo, 2016). Their structural strength simply cannot support the heavier vehicles. The Swedish Transport Administration (2019a) envisions all BK1 roads to be upgraded to BK4 in the future.

Aside from the public road network, there's an extensive private road network vital to biomass transport. 86% of forest raw products (roundwood and forest residues) are collected at private roads (Davidsson & Asmoarp, 2019). The private road network is generally subsidized by the government and open for public traffic (Swedish Transport Administration, 2019b). These roads lack any records of classification in terms of maximum vehicle gross weight or axle load, but due to them being custom built for the purposes of the originator they are considered as BK4 roads in this study.

The Swedish road network is digitally represented in the forestry version of the National Road Database (SNVDB). In SNVDB, the road network is made up of road links connected to each other with nodes in a network (Figure 3). Each link is unique and carries additional information aside from its spatial attributes, such as road number, speed limit, road width, whether its placed in urban areas or not, etc. This digitized network is a representation of the physical road network and can be used in a geographical information system (GIS) application for spatial and network analysis.

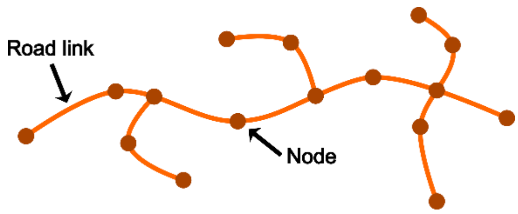


Figure 3. A schematic example of a road network containing road links connected by nodes.

1.4 Bridges

Approximately 1 400 of Sweden's more than 20 000 bridges are restricted for use with a 90-t vehicle set and cannot be crossed by them (Haraldsson et al., 2012). These are mostly located in the areas in and around Stockholm and Gothenburg but also along the east coast on roads going in north-south (and vice-versa) directions. Generally, fewer restrictions apply for bridges on roads going west to east towards the coast. Depending on the road network and geography, bridge restrictions can have varying degrees of complication for routing an HCT transport. Information about a certain bridge's structural strength is however classified information.

1.5 Previous studies

Haraldsson et al. (2012) analysed the socioeconomic effects of 90-t roundwood transport deployment. Cost based on distance for different road vehicle sets was used to do wood flow analysis using the system modelling tool Samgods and SNVDB, followed by cost calculations on a national scale. Samgods is a modelling tool for system studies of Swedish cargo transports, supporting effect analysis of policy changes, various regulatory incentives, and infrastructural changes. The analysis assumed a substitution of all conventional roundwood transports with 90-t vehicles. With a simulation discarding bridge restrictions, transport work would decrease by 21%, which would result in an overall socioeconomic cost reduction by 4

% or €15.9 M. With bridge restrictions considered, the socioeconomic effect would instead be a cost increase by 15% since the trucks had to choose longer routes to get around the bridges with restrictions for 90-t vehicles. The study concluded bridges to be a bottleneck for system-wide HCT deployment but that using HCT on well-chosen routes would probably be socioeconomically beneficent.

Lööf (2015) simulated the effects of the introduction of 74-t HCT trucks in northern Sweden on roundwood train transport. The analysis showed that train transport utilization decreased by 2.61% while still rendering positive effects on costs and GHG emissions which were reduced by 9.0-10.0% and 6.6-7.3% respectively. Similarly, Adell et al. (2016) performed a systematic analysis of how the introduction of 74-t HCT would affect the environment, industry and community. Results showed that, in many scenarios, implementation of HCT would decrease the amount of performed transport work by up to 12.0% compared to conventional 60-t truck transport. The effects should be lower when considering that the conventional truck weight from year 2016 is 64 t. This enabled higher efficiency in the transport sector which would decrease the impact on climate and lower the cost of transport increasing competitiveness in the industry. The authors did, however, find that this increased efficiency could displace transports from train to trucks and thereby cancelling the potential reduction in GHG emissions. Complementary economic countermeasures to cancel this displacement were suggested when implementing HCT and the authors emphasized the risk of conflict of interest between environmental and economic goals.

Näslund (2017) analysed how a fleet with a mix of conventional and 74-t HCT trucks would impact each other's routing abilities. Different mixes were optimized on the networks potential BK4 roads. The results showed that too big share of HCT trucks (more than 12.5% of the fleet) would increase trucking costs and GHG emissions, it was therefore important to direct HCTs to appropriate routes.

Svensson (2017) set out to improve the information hub for the Swedish forestry industry, SDC, regarding its calibrated route finder (CRF).The CRF is used for finding best-practice transport routes with respect to both quantitative factors (distance, road class, road width) and qualitative factors (stress, traffic safety). More information concerning hilliness and curviness of roads along with improved consideration of illegal turns were added to the system. The resulting road network also calculated time and fuel costs at intersections, something that could be used for route optimization regarding fuel costs and GHG emissions. In the thesis, a comparison between shortest path, fastest path, and CRF regarding several attributes, including average distances, curviness and hilliness was presented. Svensson (2017) concluded that while the path chosen by the CRF was often not the fastest nor the shortest path, it involved less time/distance on lower quality roads, gravel roads, and narrower roads and also had less curvature and hilliness in most cases. These attributes of CRF-paths amounted to transport more inclined to reduce costs while considering social values such as road safety, avoidance of traffic build-up and working environments for the truck drivers.

Korpinen et al. (2019) presented a dynamic simulation model developed to generate information about the impacts of substituting parts of the present Finnish pulpwood transportation system with HCT vehicles with default payloads of 52 t and 68 t. The results indicated that in the studied area, HCT had limited potential to reduce transport costs (2%, or €1 M, at 10% substitution) but to significantly decrease traffic intensity (12.6-14.1% of total distance savings) – all largely dependent on the configuration and balance of HCT and regular trucks. Thus, the authors concluded that a relatively small increase in HCT trucks over time would yield a continuous positive system impact, which also is the probable way of future implementation.

Previous studies generally substituted conventional trucks for HCT in various degree or analysed systemic effects of HCT deployment, but to date there are no analysis made for GHG emission- and/or cost reducing HCT corridor identification based on a flow network.

1.6 Objectives of the study

The objectives of this study were to identify potential HCT corridors for 90-t roundwood trucks on the Swedish road network based on 2016 transport data. The use of these corridors should render economic and environmental benefits regarding trucking cost (Euro/t) and GHG emissions per weight roundwood (kg CO_2/t) compared to 74-t trucks. The potential for HCT transport was to be quantified in trucks per corridor and collectively.

The following research questions were to be answered:

- How many potential roundwood HCT corridors are there in Sweden?
- How are these distributed in the different landscape regions?
- How many HCT vehicles can populate these corridors?
- How many corridors share common road traffic, making it possible to create an HCT cluster?
- How can the annual trucking distance, fuel consumption, greenhouse gas emissions and transport cost change with the use of HCT in the individual roundwood corridors per landscape region and Sweden as a whole?

1.7 Delimitations

The study did not account for: backhauling; the option for an HCT truck to drive unloaded or with less load on lower class roads; net weight restriction of bridges; annual wood flow variation; CO2 emissions from proposed terminals; gross weight or axle load restrictions on private roads.

2 Materials & methods

2.1 Workflow

In order to identify potential HCT corridors the following workflow was used (Figure 4):

- Identifying a technically supportive network, i.e. the road links able to support the gross weight of a 90-t HCT vehicle.
- Identifying flow supporting corridors on the technically supportive network, i.e. the cohesive road links able to employ at least one 90 t HCT vehicle on yearly basis.
- Using a CRF to route relevant transports both directly from the landing to the receiver and via the corridor, gathering drive distance information.
- Calculating both direct and via-corridor fuel consumption for all transport in close vicinity to the flow supportive network.
- Quantifying the flow supportive network for CO_2 beneficiality, i.e. analysing CO_2 -saving potential in the corridors.
- Identifying terminal supportive corridors on the flow supportive network, i.e. the corridors with enough cost-reducing potential to finance terminal establishment.

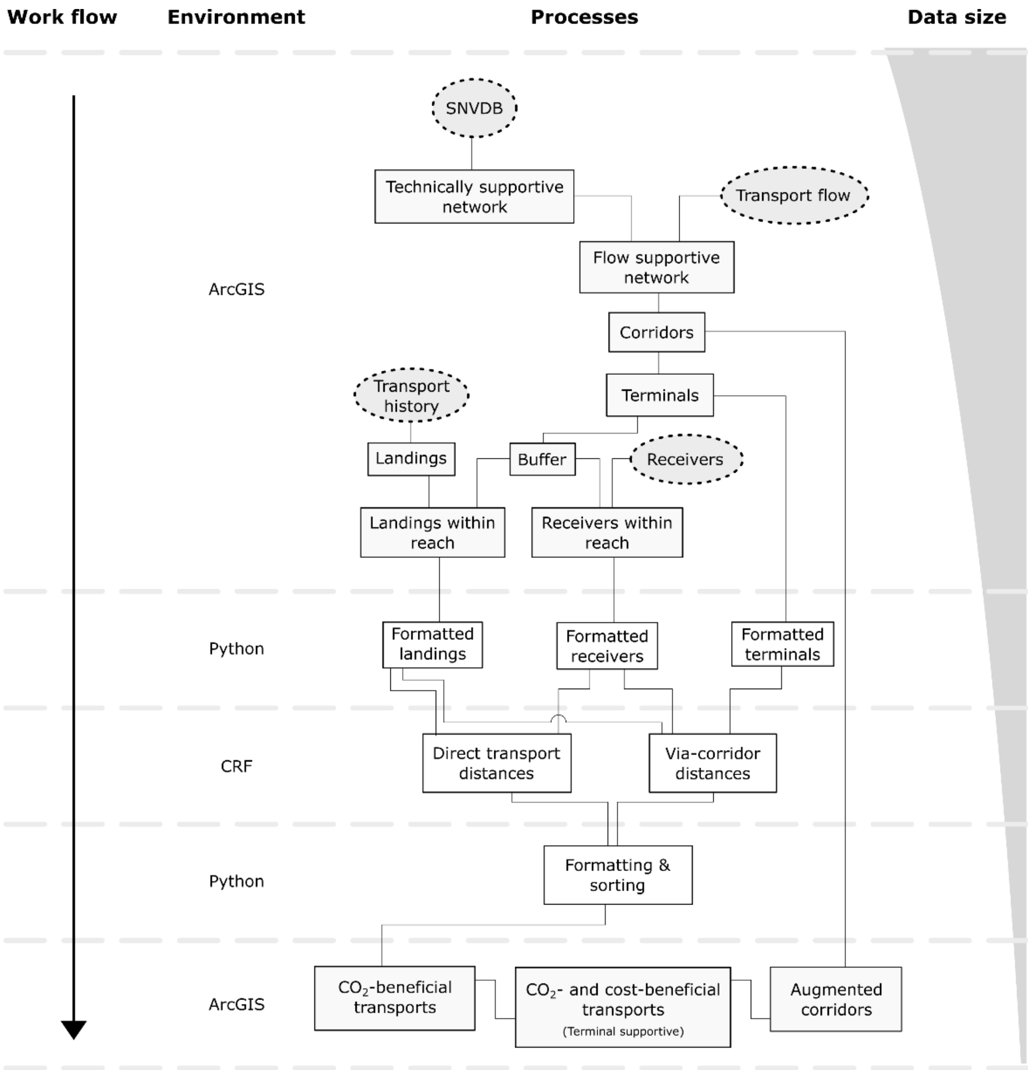


Figure 4. Schematic workflow of the study method, environment used, processes and data size. Ellipses are input data, rectangles are process-derived results.

2.2 Input data

The input dataset was 2016 transport data (Figure 5), positions of receiving locations, and the SNVDB (Table 2).

Table 2. *Type of input data used in the study. All data delivered by Skogforsk and presented in the SWEREF99 coordinate system.*

Source	GIS data ty	
Transport flow	Line featur	ısported roundwood for 2016.
Receiving locations	Point featu	tion of receiving locations.
Transport history	Table	ɔr 2016 roundwood
SNVDB	Line featur	›patial and additional infor- ł class.

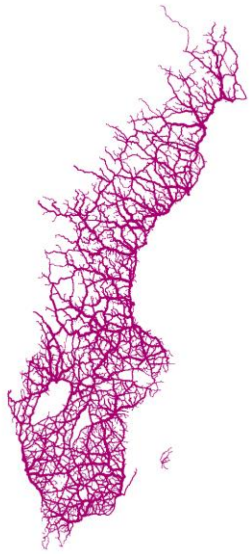


Figure 5. Schematic illustration of the flow of roundwood road transport in 2016. Thicker lines represents higher flow intensity. Processed from Skogforsk.

2.2.1 Transport data

The transport data was collected by SDC and delivered by Skogforsk and contained information about 1.34 million forest raw material transports in Sweden 2016, of which 1.28 million were roundwood transports. The roundwood transport share of forest raw material transport work was 95%. The records show landing ID, landing coordinates (SWEREF99), assortment (roundwood, chips, primary biofuel), transported weight (metric ton, t) and receiver ID for each transport.

2.2.2 Receiving locations

The dataset for receiving locations was comprised of 2381 records of locations in Sweden with receiver ID, coordinates, name and receiver type (e.g. industry, terminal, harbour), of which 2003 were spatially unique.

2.3 Technically supportive network

To find the network technically compatible with 90-t HCT, all SNVDB road links with road class BK1 or BK4 as well as private roads were sorted out to be included in an independent technically supportive network (Figure 6). Satellite road links in the new network not able to connect to any receiving locations were removed.

Figure 6. Schematic illustration of workflow for finding the technically supportive network. Left: Section of SNVDB with BK4, BK1 and private roads in purple and others in red. Centre: Just BK4, BK1 and private roads remain, satellite roads are highlighted in red. Right: Resulting cohesive technically supportive road network.

2.4 Flow supportive network

A potential HCT corridor must be able to employ at least one 90-t HCT truck with enough annual transport work to keep it from being idle. The length of the corridor dictates the need for annual roundwood flow volume in order to qualify as a flow supportive route. With longer transport distance between loading and unloading locations, a truck will take fewer turns within a time frame making the required flow volume inversely exponential to the transport distance. The required annual roundwood flow (t) for a given distance (km) was calculated as:

$$Q_a = \frac{c_c * h_a}{h_l + \frac{d}{s_l} + h_u + \frac{d}{s_u}} \qquad (1)$$

Where

Q_a: Annual roundwood flow, ton

c_c: Cargo capacity, ton

h_a: Annual work, hours

h_l: Loading time, hours
h_u: Unloading time, hours
d: Distance, km
s_l: Average speed, loaded, km/h
s_u: Average speed, unloaded, km/h

To set the cut-off values for a corridor to be flow supportive for different transport distances (Figure 7) the following assumptions for HCT trucks were made: in use two shifts per day, eight hours per shift, seven days a week for 50 weeks per year; has an average roundwood net weight of 65.1 t (Brunberg & Hofsten, 2018); average speed of 75km/h; loading/unloading time of 0.5 hours each.

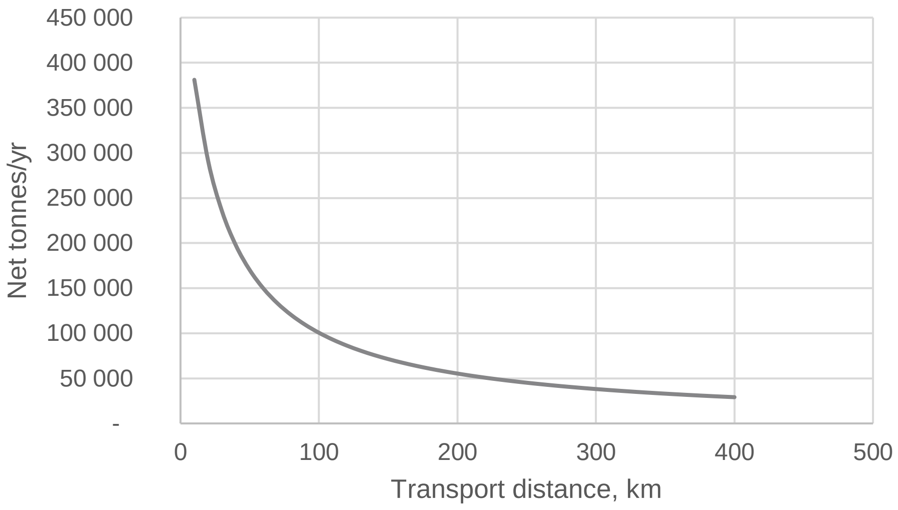


Figure 7. Cut-off values for flow supportive corridors as a function of one-way transport distances, derived from formula (1). Simplified regression fit: 3E6*$x^{-0.77}$, R^2=0.9853

For a corridor to be flow supportive, its net tonne flow must equal or exceed the cut-off value of the function of its transport distance (Figure 7).

2.5 Transport flows

Two ways of transporting using corridors were conceptualized: duplex transport flows and multiplex transport flows.

2.5.1 Duplex transport flow

A duplex transport flow was defined as a flow between two nodes in an HCT transport system. These nodes could be sources or sinks, depending on the route. One example of this is a converging flow of roundwood from small deposits in the forest going to the same industry for processing (Figure 8). A terminal could be established at the converging node, facilitating an HCT corridor between the terminal and the industry. The total transport would then be divided in two legs of transport.

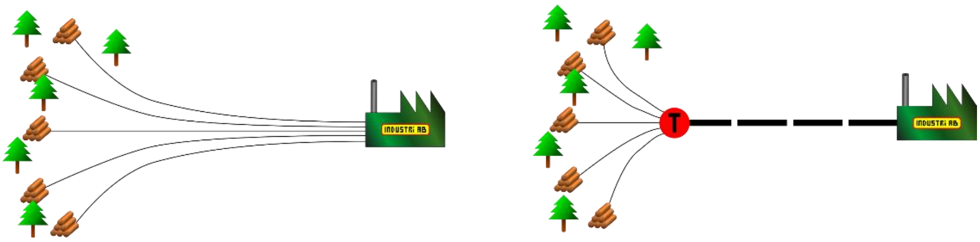


Figure 8. Converging flow with conventional transport (left) and with an HCT corridor (right).

Another example of a duplex transport flow is a diverging flow of roundwood with the same source, for example a train terminal, to several industries (Figure 9). A terminal could be established at the diverging node, facilitating an HCT corridor between the train terminal and HCT terminal.

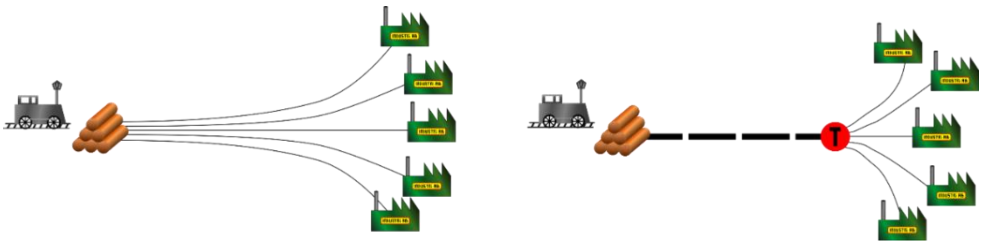


Figure 9. Diverging flow with conventional transport (left) and with an HCT corridor (right).

The principle of an HCT transport system with a duplex configuration was valid when the entire flow through one node were to be received by another (Figure 10):

$$f_i = f_t \tag{2}$$

Where
f_i: flow at industry, t/year
f_t: flow at terminal, t/year

The flow between two nodes cannot exceed the flow of the smallest part in the chain keeping them together. In the context of the transport stream, this means the smallest flow at the links along a potential duplex HCT corridor, i.e. the route between nodes ft1 and ft2 (Figure 10), dictates the overall flow F of the corridor, and was defined as:

$$F = \min(f_a, f_b, \dots) \tag{3}$$

Where
F: overall corridor flow, t/year
f_a: flow at link a, t/year
f_b: flow at link b, t/year

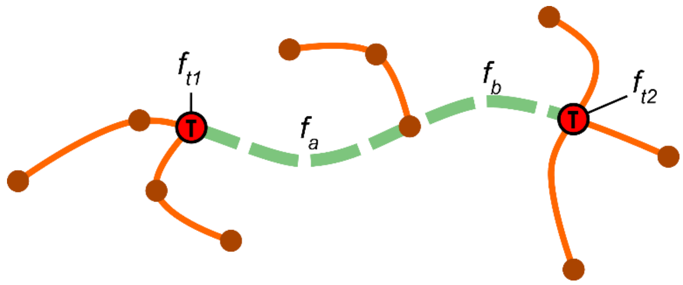


Figure 10. Schematic illustration of the road links in a duplex HCT corridor. The green line symbolizes a potential HCT corridor between two nodes. Orange lines are other roads in the network, orange circles are other nodes in the network.

2.5.2 Multiplex transport flow

Unlike a duplex route, a multiplex configuration was defined as having more than one flow sources or sinks on both ends of the potential HCT corridor (Figure 11), resulting in a need for an additional leg of transport (i.e. both on the source- and sink side of the corridor) as well as a second terminal.

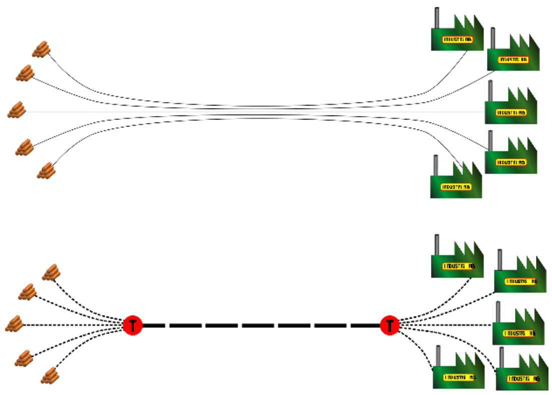


Figure 11. Converging-diverging flow with conventional transport (upper) and with a multiplex HCT route (below).

2.6 Generating a flow supportive network and corridors

The flow of the links in the technically supportive network were compared to the cut-off curve (Figure 7). Isolated and short segments of links (<50km) were removed. The remaining flow supportive segments were then included in a new flow supportive network. The individual flow supportive segments were considered potential 90-t HCT corridors

2.7 Mining direct and via-corridor distances

Using the Krönt Vägval CRF (Svensson, 2017), transports occurring in the vicinity of each potential HCT corridor were re-routed both directly from the landing to the receiver and via the corridor to generate driving distances. The driving distances were then added back to ArcGIS and superimposed onto the flow supportive network. The selection of transports mined for distance information was limited with GIS buffering due to data processing and computing time restrictions. A circular buffer area with a radius of 50 km around the end vertexes (terminals) of the corridors was used. The limited selection of transports was considered being in reach of the model. A standard desktop PC with a 4 core, 4 thread 3.8GHz clock speed Intel processor and 16 GB of RAM was used. Since the CRF supported only one set of transport origins to one set of destinations at a time and demand specific formatting rules, Python 3.7 was used to prepare and batch process each corridor's input data derived from ArcGIS Pro 2.3 (Figure 12).

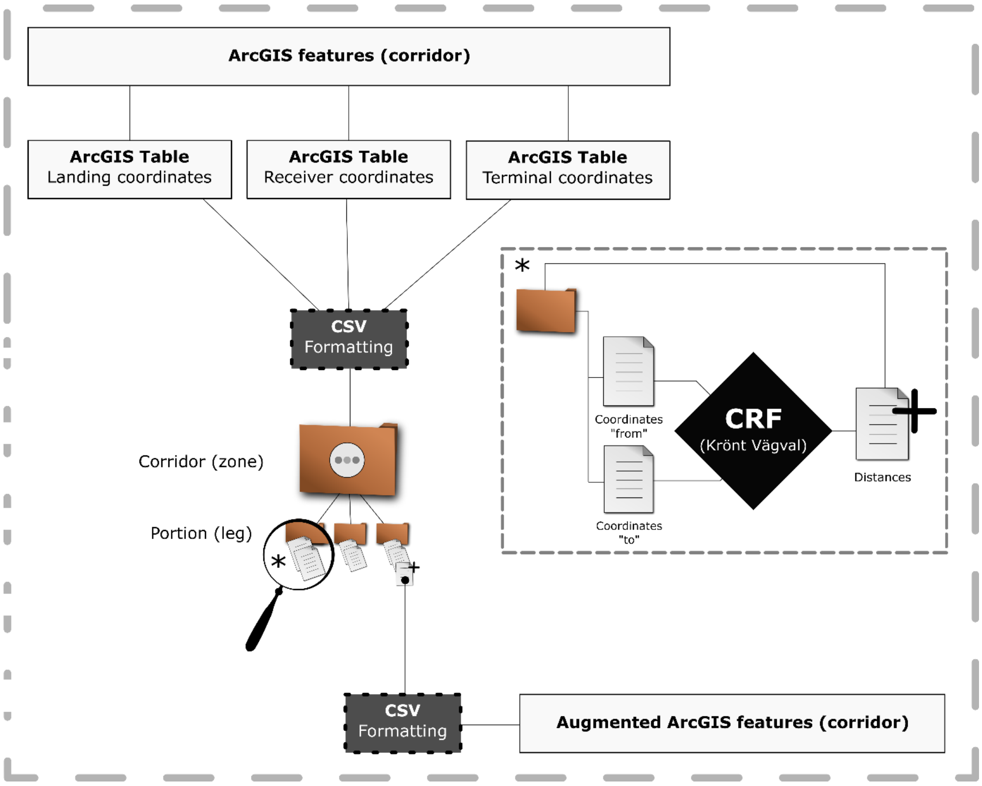


Figure 12. Schematic workflow of the script designed to iteratively mine drive distances for corridors. Landing-, receiver- and terminal coordinates were hierarchically structured by corridor and leg before being fed to the CRF. Results were then collected from the leg folders to augment the corridor features.

2.8 Fuel consumption

Average fuel consumption for a 74-t and 90-t truck transport work was set to 0.028 and 0.019 L/tkm, respectively, according to Brunberg & Hofsten (2018). With each transport having direct and via the corridor distances (Figure 13), the fuel consumption for a 74-t direct transport was:

$$a_{74} = d_d * \mathrm{q} * 0.028 \qquad (4)$$

Where
a_{74}: Fuel consumption for 74-t truck for direct flow, L
d_d: Distance for direct flow, km
q: Quantity at landing, t

The HCT transport via the corridor is comprised of three legs: 74-t forwarding to the first terminal, 90-t corridor transport and, in the event of a multiplex corridor, a 74-t transport to industry gates:

$$
\begin{aligned}
a_{90} = {} & d_a * q * 0.028 + d_c * q * 0.019 + d_b * q * 0.028 = \\
& = q(0.028 d_a + 0.019 d_c + 0.028 d_b)
\end{aligned}
\tag{5}
$$

Where
a_{90}: Fuel consumption for via-corridor transport, L
d_a: Distance landing to first terminal, km
d_c: Distance of the corridor, km
d_b: Distance from second terminal to industry gates, km

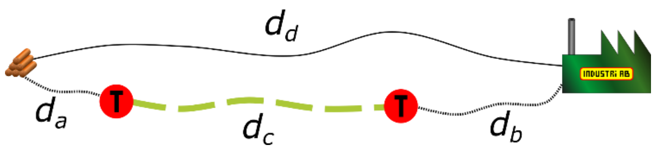


Figure 13. Illustration of transport legs in a direct flow (dd) and a via-corridor multiplex flow (da+dc+db).

Fuel consumptions were calculated for both direct and via-corridor transport for every transport in the flow supportive network. In the event of a duplex corridor, where the corridor extended all the way to the receiver, the last leg of transport (from corridor to receiver) was redundant and fuel consumption for that leg zeroed.

2.9 CO2-beneficial transports

To get GHG emission data from the fuel consumption, a factor of conversion was used. Average GHG emissions of diesel (MK1) in a life cycle perspective was reportedly 2.81 kg CO2 per 1 L diesel (Swedish Energy Agency, 2017). The transports where via-corridor transport showed lower CO2 emission than direct transport were included in a new CO2 beneficial network.

2.10 Terminal supportive transports

The system cost of a HCT corridor includes more cost items than a conventional system. HCT vehicles by themselves have some higher costs, both fixed and variable, than conventional vehicles such as in investment, taxes, insurance, service and repairs (Johansson & Hofsten, 2017). Aside from these vehicle-specific costs, HCT corridor costs also include transport to and from terminals and terminal-related costs (Figure 14). For the conventional system, transporting directly from one point to another, the only cost item is the transport itself.

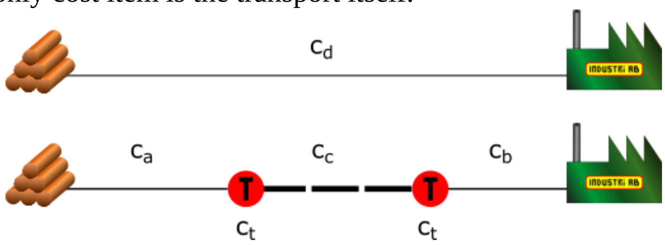


Figure 14. Cost items in a conventional (top) and HCT system (bottom).

For an HCT route to be considered cost efficient, its system cost should be equal to, or lower than, the conventional system cost for the same route:

$$c_a + c_t + c_c + c_t + c_b \leq c_d \qquad (6)$$

Where
c_a: Transport cost from landing to terminal, €
c_t: Terminal related costs, €
c_c: Corridor transport cost, €
c_b: Transport cost from terminal to receiver, €
c_d: Direct transport cost, €

In a situation where an HCT corridor would serve only one receiver, the receiver terminal could be cancelled and instead have the HCT corridor go all the way to the receiver itself. This would add some distance and cost to the corridor transport but eliminate the cost of transport from terminal to receiver as well as for the terminal itself.

2.11 Transport costs

Transport cost for direct and via-terminal transports were calculated with the fuel consumption and a diesel price of €1.55 per L.

2.12 Terminal related costs

The establishment and running costs of a new terminal is object to variation due to differences in location and roundwood flow in every potential HCT corridor. The area related costs of terminal establishment consist mainly of land acquisition cost and construction cost (Virkkunen et al., 2015). Land can be acquired through purchasing, renting or leasing. It's hard to generalize such a cost item since the price of land greatly differs depending on location, but a common value for renting in a rural area used by Virkkunen et al. (2015) was about €1000/ha/year corrected to today's monetary value. With land acquired, construction is a cost item dependant on the surface treatment. Asphalting on top of existing gravel costs about €20 to €30/m^2 and if additional land construction is needed prior to paving, that cost could be over three times as much (Virkkunen et al., 2015). This study generalized lifetime expectancy of an asphalt terminal surface to 30 years, resulting in an annual construction cost of €1 per m^2. Connecting roads and rail to a terminal is also a big cost item but is not always constructed by the terminal operator or could be strongly subsidized. As in the study by Virkkunen et al. (2015), this study did not account for these costs.

A terminal establishment as proposed in this study was a simple one. Since there were no measuring or processing of the roundwood at these terminals, only the bare minimum of facilities was needed. A flat gravel or asphalt surface and a wheel loader for loading the HCT vehicle was needed. The size of the terminal was determined by the transport flow through it and the stock turnover within it. The turnover was an expression of buffer, where one day's turnover is zero buffer: the roundwood is deposited and collected the same day whereas, for example, a five-day turnover holds five days' worth of roundwood without collecting before filling up. A faster turnover would reduce establishment costs by utilizing a smaller space while a slower turnover would allow for buffering of the roundwood which could be helpful in route planning, especially in clustered HCT corridors.

The space needed to store roundwood in this proposed fashion depended on the dimensions and shape of the piles in the terminal, as well as the space between them. In accordance with Virkkunen et al. (2015), terminal storage capacity with piles 6 m wide, 5 m high and with 6 m passageway in between, was generalized to about 1.25m^3/m^2.

To generalize, stock turnover was used in tandem with the roundwood flow to calculate the size, and therefore establishment cost, of the terminal:

$$c_{est} = \left(\frac{r_a/d_a * t}{s_c}\right)(c_a + c_{con}) \tag{7}$$

Where
c_{est}: Terminal establishment cost, €
r_a: Annual roundwood flow, m3

d_a: Annual available workdays
t: Stock turnover, days
s_c: Terminal storage capacity, m^3 per m^2
c_a: Land acquisition cost, € per m^2
c_{con}: Construction cost, € per m^2

In addition to the establishment of a terminal, costs are generated with continuous handling at the terminal. Depending of the design, flow and size of the terminal, these costs may vary significantly. In this study, a generalized tariff for wheel loader cost per cubic meter based on Virkkunen (2015) was used (Table 3). The tariff was based on an hourly cost of €56.64 and a productivity of 160 m3/h, and since roundwood is both unloaded and loaded (or vice versa) at a terminal, the tariff was doubled.

These generalized terminal related costs (Table 3) in an HCT system were implemented as a function of roundwood flow and desired stock turnover to generate the terminal cost unit (c_t):

$$c_t = c_{est} + c_w r_a \tag{8}$$

Where
c_w: Wheel loader tariff

Table 3. *Summary of properties and values used to calculate terminal-related costs in the study.*

Variable	Property	Value
s_c	Terminal storage capacity	1.25 m^3 roundwood per m^2 terminal area
r_a	Annual roundwood flow	Corridor-specific
d_a	Annual working days	350[1]
c_a	Land acquisition	€ 0.1 per m^2 terminal area per year
c_{con}	Land construction	€ 1 per m^2 terminal area per year
t	Stock turnover	5 days
c_w	Wheel loader tariff	€ 0.71 per m^3 roundwood

[1] 7 days a week, 50 weeks per year = 350 days

2.13 Cost superimposition

The cost data for each transport were superimposed onto the flow supportive network. The transports where a 90-t HCT system cost was equal or lower than the 74-t conventional system cost were selected to form a terminal supportive network. This network was generalized to have the economic potential of being HCT corridors.

2.14 Regional distribution

To identify corridor distribution in the regions of Sweden, a relevant system for that was needed. In the European Union, the Nomenclature of Territorial Units for Statistics (NUTS) system is used for geographic distribution of statistics (SCB, 2008). In Sweden, NUTS-1 is used for the three major regions, NUTS-2 for national areas, and NUTS-3 for counties. This study used the NUTS-2 for corridor distribution (Figure 15) as this was a subjectively suitable resolution for regional analysis. Each corridor was appointed a NUTS-2 "owner" based on spatial relationship. In the case of a corridor crossing two or more national areas, the corridor's ownership went to the national area containing the majority of the corridor's distance.

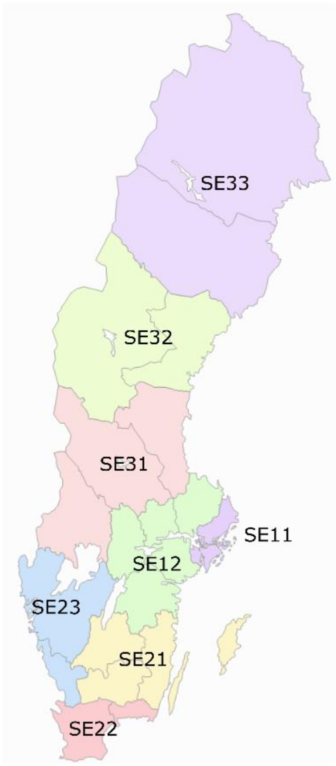


Figure 15. National areas of Sweden.

2.15 Clusters

Clusters enable corridors with insufficient flow to group and collectively utilize 90-t HCT trucks. Cluster compatibility was considered true for a corridor when at least one of its endpoints (terminals) were adjacent another corridor's endpoint.

2.16 Quantification

Each corridor's roundwood flow (Equation 3) on the terminal supportive network is divided with its 90-t flow requirement (Equation 1 1) to quantify the number of vehicles that potentially could be deployed on the corridor with a GHG and fuel cost benefit when compared to a conventional 74-t truck system.

3 Results

3.1 Overview

Results are presented in the order of the method, where results are continuously processed from the large road network in part 3.1 to the final terminal supportive transports in part 3.5. Throughout the processing and funnelling of data, the transport work accepted by the model according to the method and its restrictions decreased (Figure 16).

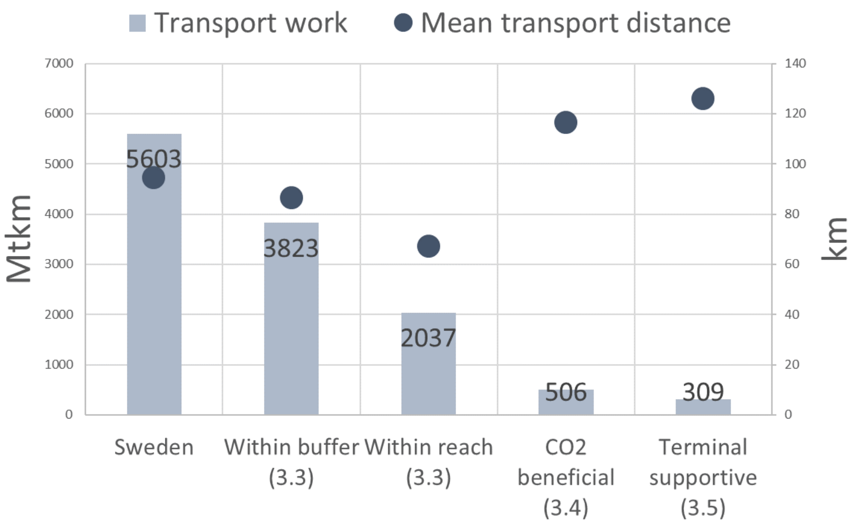


Figure 16. Transport work and mean transport distance for roundwood transport in the different stages of the study.

3.2 Technically supportive network

BK1 and BK4, the two road classes defined to be able to carry a 90-t HCT truck, make up 20.4% of the all road links (public and private) in SNVDB; with private roads included as technically supportive the technically supportive network grew to include 96.9% of all road links.

3.3 Flow supportive network

25 potential multiplex HCT corridors were identified (Figure 17). 12 of the corridors either shared or had a terminal within a distance of 2 km (Euclidean) from another HCT-corridor's terminal and were considered cluster compatible. Of the 3823 Mtkm transport work carried out within the buffered area around the corridor's terminals, 55% were viable for analysis, having both the landing and receiver within the buffered area (within reach of the model).

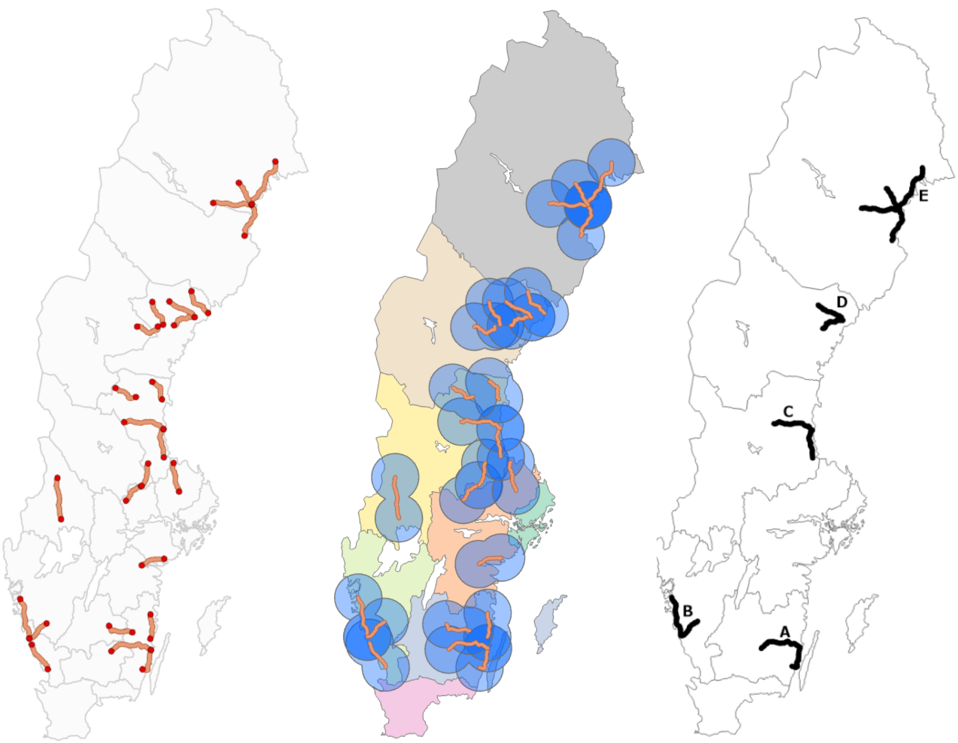


Figure 17. Left: Potential HCT corridors (orange) and their connected terminals (red). Middle: Buffer areas (blue) around corridor's endpoints (terminals). Right: identified clustered corridors.

The mean corridor length was 69.1 km with median being 62.2 km and the shortest and longest being 50.9 km and 115.3 km respectively (Figure 18). Total length of all corridors was 1726.3 km.

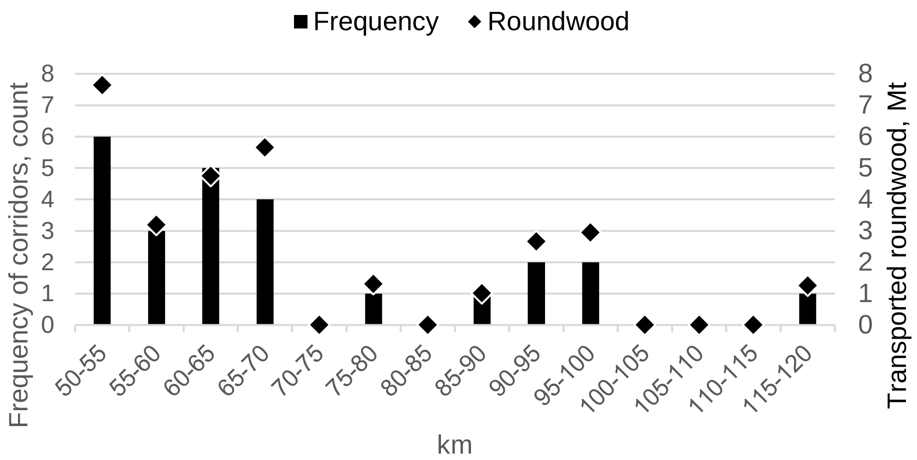
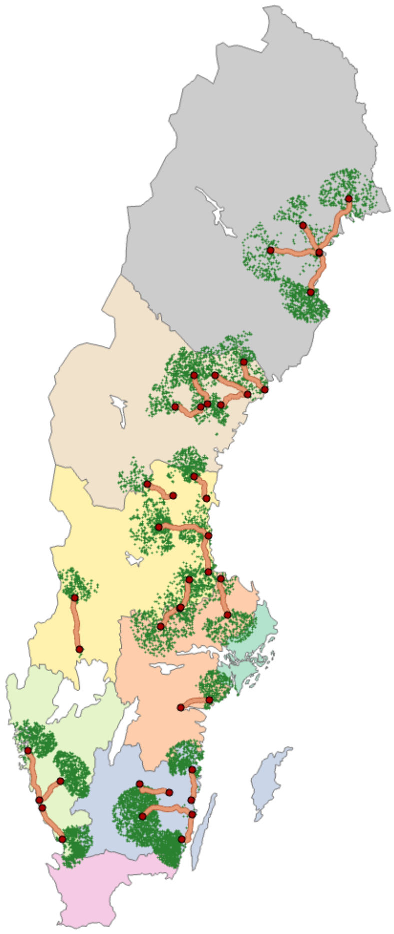


Figure 18. Frequency distribution and amount of roundwood transported (within reach of the model) by HCT corridor length. Left Y-axis is number of corridors, right Y-axis is amount of transported roundwood (Mt) and X-axis is length of corridors (km).

For transports within reach of the model the average transport distance was 67.2 km with median being 61.8 km and the shortest and longest being 0.1 km and 212.9 km respectively.

3.4 CO_2 beneficial transports

For transports within reach of the model, starting and ending within a 50 km buffer radius around the terminals of the HCT corridors, 29% of the transport work was shown being environmentally beneficial regarding CO2-emissions when routed via 90-t HCT corridors instead of being driven by 74-t trucks directly to receivers (Figure 16, 19). The use of corridors for those transports were shown to save 2.43 M liters of fuel, saving 17.2% of CO2 emissions by those transports in conventional 74-t transport. With all transports within the reach of the model considered, the use of corridors was shown to save 5.1% of 74-t CO2 emissions (Table 4)



Figur 19. Overview of HCT corridors (orange lines), terminals (red), landings for transports with CO2 benefit when routed via-corridors instead of directly to receivers (green).

For costs, the use of corridors where environmentally beneficent regarding CO2 emissions was shown to save 17.2% (€3.8 M) in fuel consumed by those transports and 5.1% of all 74-t transport fuel consumption within reach of the model. The terminal related costs (acquisition, establishment, handling) was €3.2 M, lowering net savings to €0.6 M.

Tabell 4. *Potential reductions in CO2 emissions and fuel costs (after superimposed terminal costs) for the CO2-beneficial via-corridor transports.*

NUTS-2 code	NUTS-2 name	Emission reduction potential, t CO_2	Cost reduction potential, thousand €
SE11	Stockholm	-	-
SE12	East middle	505	-64[1]
SE21	Småland and the islands	1416	245
SE22	South	-	-
SE23	West	764	2

SE31	North middle	1891	220
SE32	Middle Norrland	1054	17
SE33	Upper Norrland	1192	193
sum		*6822*	*613*

[1] cost was increased

Basic statistics of potential savings in cost and CO2 emissions of via-corridor transported roundwood where CO2-beneficial are presented in Table 5.

Table 5. *Potential savings in kg CO2 and Euros for CO2-beneficial via-corridor transports.*

Variable	Mean	StDev	Minimum	Median	Maximum
Kg CO_2 saved/t	1.57	1.15	0.01	1.36	5.82
€ saved/t	0.15	0.63	-0.72	0.04	2.49

3.5 Terminal supportive transports

With terminal related costs superimposed onto the CO2 beneficial transports, 60.8% of that transport work was found being terminal supportive (Figure 16, 20). Routing only these transports via corridor lowered CO2 emissions by 4.1% of all 74-t transports within reach of the model. Fuel costs were lowered by €3.1 M, or 14.0%, compared to direct driving the CO2 beneficial routes with 74-t trucks (Table 6). The cost of terminal handling for these transports was calculated to €1.8 M, resulting in net savings of ca. €1.3 M.

Table 6. *Potential reductions in CO2 emissions and fuel costs (after superimposed terminal costs) for the terminal supportive via-corridor transports.*

NUTS-2 code	NUTS-2 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*

Basic statistics of potential savings in cost and CO2 emissions of via-corridor transported roundwood where CO2-beneficial and terminal supportive are presented in Table 7.

Table 7. *Potential savings in kg CO2 and € for CO2-beneficial and terminal supportive transports over the corridors.*

Variable	Mean	StDev	Minimum	Median	Maximum
Kg CO_2 saved/t	2.28	1.07	1.31	1.84	5.82

€ saved/t	0.54	0.59	0.01	0.29	2.49

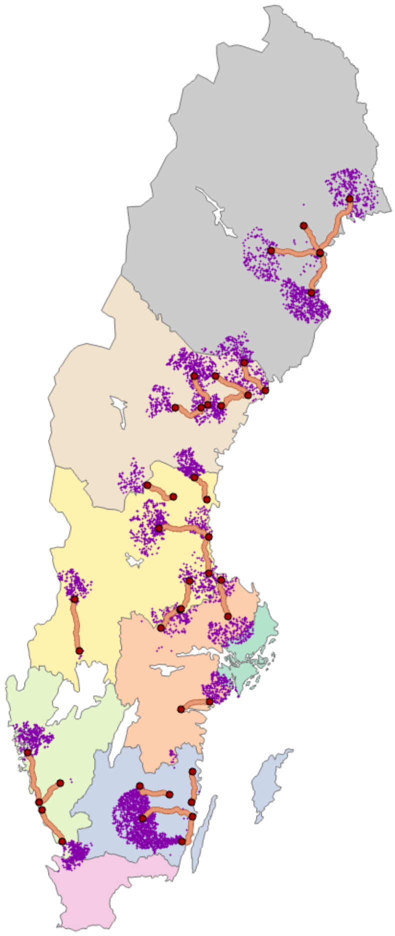


Figure 20. Overview of HCT corridors (orange lines), terminals (red) and landings for terminal supportive via-corridor transports(purple).

3.5.1 HCT quantification

Nine corridors were shown being able to employ at least one 90-t HCT truck on the terminal supportive network while five corridors had little to no (<0.3 trucks) ability to support employment (Table 8). The remaining 11 corridors had moderate (0.3 - 0.9 trucks) ability to support 90-t HCT truck employment. The five identified potential corridor clusters were all able to support 90-t HCT employment, with the lowest and highest quantification being 1.2 trucks and 3.7 trucks respectively.

Table 8. *Potential 90-t HCT corridors, cluster properties, roundwood flow and approximate vehicle quantification.*

Corridor ID	National area	Potential cluster property	Lenght, km	Roundwood flow, t	Q_a[1], t	90-t HCT quantification
8	SE12		53,6	68 591	150 085	0,5
10	SE12		50,9	1938	154 597	0,0
12	SE12		65,7	90 728	132 474	0,7
1	SE21	A	56,9	74 206	144 879	0,5
2	SE21	A	99,4	267 524	99 826	2,7
4	SE21		54,4	3608	148 732	0,0
7	SE21		62,2	0	137 122	0,0
3	SE23		64,9	93 885	133 486	0,7
5	SE23	B	91,0	126 476	106 400	1,2
6	SE23	B	52,7	248	151 489	0,0
9	SE31		92,1	67 274	105 494	0,6
11	SE31		53,6	87 344	150 137	0,6
13	SE31	C	68,4	194 528	129 068	1,5
14	SE31	C	95,3	194 481	102 939	1,9
15	SE31		53,8	212 182	149 768	1,4
16	SE31		55,7	45 440	146 611	0,3
17	SE32		61,5	89 453	138 055	0,6
18	SE32		60,1	128 269	140 131	0,9
19	SE32	D	60,8	151 586	139 115	1,1
20	SE32	D	67,9	101 872	129 747	0,8
21	SE32		68,4	94 614	129 042	0,7
22	SE33	E	78,3	126 183	118 105	1,1
23	SE33	E	85,8	114 586	110 890	1,0
24	SE33	E	115,3	141 085	89 451	1,6
25	SE33	E	57,6	283	143 728	0,0
sum				*2 476 384*		*20,5*

[1] *from equation 1*

3.5.2 Transport flow

Direct transport of the identified terminal supportive transports accumulated to 12.88 M vehicle-km. With routing these transports via corridor, the traffic flow was increased to 16.84 M vehicle-km or by 30.8%. A slight majority of the transport work of the terminal supportive transports was performed on the HCT corridors while the remainder was performed by 74-t trucks either between landing and terminal or terminal and receiver (Figure 21).

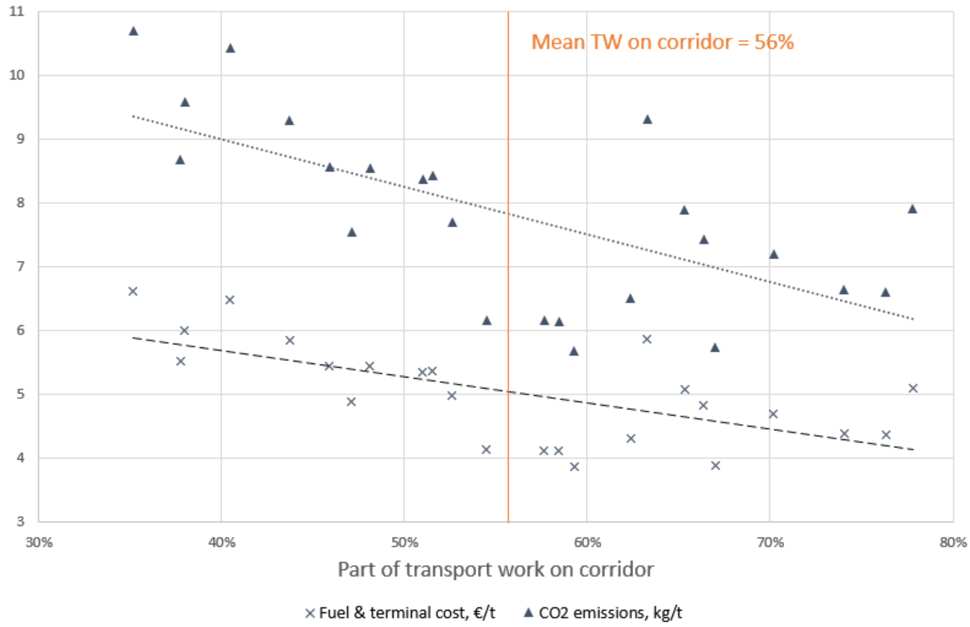


Figure 21. Identified corridor system's cost and emissions (y axis) compared to how much of the corridor system's transport work was accommodated by the HCT corridor itself (x axis).

The terminal supportive mean transport distance was 125.8 km, or 33% higher than the national mean. The terminal supportive transport work was shown to account for 5.5% of the national total roundwood transport work.

4 Discussion

4.1 Method

74-t trucks were used as a base for comparison to the 90-t HCT trucks, even though most Swedish real-world truck traffic is still based on a 64-t truck system. Though this certainly lowered the observable potential of 90-t trucks in this study, the credibility of the comparison increased as the fuel consumption functions used were derived from the same study using the same methods for both truck systems (Brunberg & Hofsten, 2018). It also highlights future potential and could still be relevant if 74-t trucks constitute a majority of the transport fleet. It can be recommended for future studies to investigate how the potential changes with even larger trucks.

The method used in this study was original in the sense that it did not depend on methodology used in other studies. This might lower the credibility of the study since there were some factors that could be altered to potentially produce different results, such as buffer size around corridor endpoints (terminals) and the roundwood flow supportive cut-off value (equation 1). The study method differed to other studies in the way it included dynamic placing of terminals at identified corridors' end points, unlike in Korpinen et al. (2019) where the terminals were already spatially set.

Generating a flow supportive network and corridors

While generating a flow supportive network and corridors, a minimum allowed distance of the segment (corridor) of 50km was used. This was done to prevent small sections of some roads where transport flow might be especially large (intersections, roundabouts, connecting roads etc) to introduce disturbances in the following analysis. Also, it was assumed that a corridor shorter than 50 km would be less realistic to establish in the real world, even though comparative analysis could show it having cost- and CO_2-emission saving potential.

Buffer size

The buffer size of 50km used in the method to find potential corridor transports was chosen due to technical restrictions in the hardware used for the modelling. Ideally, though, this buffer size should have been bigger to capture and analyse more transports. The use of 50km buffers did, however, capture about a third of total truck transport work in Sweden.

Flow supportive cut-off value

The cut-off value to decide whether a corridor is flow supportive or not was based around general assumptions of annual work hours and driving- and loading speed. While conceptualizing this equation, the driving speed was set to be dynamic and adhering to road data in NVDB but was scrapped due to processing restrictions. If a stable solution to this would have been found it would have yielded more accurate results of corridor characteristics (length, flow, saving potentials, etc). For the assumption of annual work hours; more annual work hours would've produced fewer viable corridors and vice versa.

Terminal related costs

Similarly to the flow supportive cut-off value, the terminal related costs were generalised with assumptions and actual terminal establishment and running costs would probably differ from those found in this study due to high variability in land value and terrain characteristics. Real-world on-site logistics operations and its cost does not scale as linearly as in the model designed in this study. To increase accuracy in terminal related cost modelling, case studies for each potential HCT terminal could be recommended.

4.1.1 Terminal concept

Regarding terminals as proposed in this study, their design should not be limited by a traditional representation of what a terminal is or should be but rather be considered a buffered junction along a dynamic network. Within the nature of a biomass supply chain, where the origin (landing) variation motivates transport flexibility, these terminals or buffered junctions could range from a relatively small gravel surface next to a road to a fully-fledged traditional terminal with rail access and measuring stations. Terminal related costs were mostly due to terminal handling such as loading and unloading trucks, not so much the fixed costs of acquisition or construction. With a modular load carrier system, these costs could be marginalized while terminal area could be minimized. This would unlock further potential of reduced transport cost and emissions

4.1.2 Delimitations

Backhauling

The option of using backhauling in a transport system was not accounted for in this study. Backhauling is an important concept in trucking, where the haulage of cargo back from point of delivery to the originating point enables a trucking company to cover expenses for the otherwise empty trip back. For the HCT corridor system, backhauls could be difficult to implement in a wider sense due to its static nature. Since the HCT vehicle in a corridor system transports big volumes continuously, there could be a challenge in finding persistent backhaul flows to match, especially with current regulations only allowing these heavy vehicles to operate on a permit-applied-for-route.

The study does however suffer from excluding backhaul options for the comparing system, the 74-t system. In real-world, this more flexible system probably could generate some backhauls that would affect its trucking costs and therefore reduce the 90-t systems potential savings in both costs and CO_2 emissions.

Bridges

Most bridges restricted for 90-t vehicles are located either in the Stockholm-area or along the coast in a north-south direction (Haraldsson et al., 2012). The location of the restricted bridges are classified, so there was no way to identify corridors containing one of these bridges.

4.2 Results

4.2.1 Technically supportive network

A problem with the model concerning the construction of a technically supportive network is that bigger highway roads often were represented as multiple parallel road links in SNVDB. This enabled road links to be counted twice, possibly producing a larger than actual part of SNVDB to be included in the technically supportive network. This potential over-inclusion could however not affect results of the overall analysis, it just made the basis for following processing wider. More importantly, the parallel road links split the roundwood flow provided in the input data, leading to a potential loss of road links when filtered for a certain flow to generate the flow supportive network. This could've caused corridors along the larger roads not to materialize in the model, resulting in a underestimation of potential CO_2- and cost reduction potential in the flow network.

4.2.2 Flow supportive network

Traffic Flow

When compared to direct driving, via-corridor transports were almost always the longer route. Even though the 90-t truck carried an extra 36.8% of the roundwood capacity of the conventional 74-ton truck, the on average 30.8% longer routing of transport made the total distance travelled by all transports within reach of the model longer when using 90-t HCT's. The part of total transport work actually performed on the corridors were shown to be too low to compensate for the detour most via-corridor transports had to take compared to direct transport. An increase of transport work on corridors would lessen this increase and, at some point, reverse it to become a decrease of vehicle-km, lowering personnel costs. Road safety and social values would increase as well with fewer trucks on the road. It can be conceptualized that a longer corridor could support a bigger procurement area while still yielding a decrease in vehicle-km.

One restriction in the current transport system is the fact that all harvested forest products have a set receiver destination even before the point of harvest. Instead, with a standardized assortment and quantification specification, a product of transport could be transported to any receiver willing to accept that standard. This would soften the firm matrix of wood supply and facilitate a significant increase in beneficence regarding transport costs and GHG emissions. Some geographic exchange of roundwood is currently used between companies to reduce transport work, but this is not standardized or centralized. Usually, logistics managers call each other to arrange these deals. With standardized and open trade, the transport flow could be optimized based on supply and demand rather than streamlined for efficiency. It would be interesting to modify the model designed in this study to run such a scenario.

Clusters

5 zones with adjacent corridors were identified in this study, in which 4 corridors had an HCT quantification below 1. The adjacency could enable individual corridors with a flow insufficient for independent 90-t HCT traffic to share traffic. All 4 corridors with insufficient flow could be used in a clustered scenario. The adjacency distance used in this study only allowed for relatively close corridors to be considered clustered, whereas a wider distance would enable more corridors to be used without risking a truck to be idle. An HCT truck could very well drive around the regions and visit different corridors, essentially broadening the cluster scope to include several regions. That could be a problem in terms of personnel allocation resulting in higher costs, but with autonomy this wouldn't be a cost issue. One could identify a regulatory supportive network allowing empty HCT traffic just for connection of the corridors

4.2.3 Terminal supportive transports

Fuel costs is generalized to be about a third of the total cost in transporting roundwood in Sweden (Svensson, 2017). This study used a bare-minimum approach to terminal establishment and the terminal supportive transports were shown saving enough fuel to facilitate this establishment. In the future, fuel costs will likely increase, making terminal establishment relatively cheaper and HCT deployment even more relevant for saving costs in the transport system.

4.2.4 Global perspective

While the savings of introducing 90-t HCT corridors compared to conventional direct truck transport at a glance might seem marginal, when applied at a larger scale the effect would be tangible. Worldwide, almost 2 billion m^3 or forest biomass were harvested and by assumption transported in 2017 (FAO, 2018), or close to 30 times the Swedish harvest levels. With extrapolation of the results and assumptions presented in this study, worldwide 90-t HCT deployment on well-chosen routes could yield annual GHG emission reduction of about 165 Mt CO_2. As a reference, total annual GHG emissions from the worldwide forest products value chain were estimated to 890 Mt CO2 in 2010 (FAO, 2010).

4.3 Strengths and weaknesses in the study

4.3.1 Workflow

The workflow to target achievement in accordance to the research objective was designed in an explorative way, in the sense that a solution of one problem led to the next problem. This made it difficult to manage time. Scripting the extraction of data from ArcGIS to a folder structure followed by an iteration of feeding the CRF as schematically shown in Figure 12 proved to be harder than expected to someone without prior programming experience and could surely be made a lot more efficient by a professional. Similarly, the overwhelming amount of data processed throughout this study made it hard to identify valuable information at times.

4.3.2 Other uses of the model

At a concept level, the model designed in this study used fairly uncomplicated input data comprised of an infrastructure network, a transport flow dataset and locations of receivers. The application in this study was truck transport and was based on transport history, making results to be wise after the event. With modification, the transport history could be switched out for a transport forecast to change the application to be more of a prognostic tool for future investment in strategically placed HCT corridor solutions. Also, the model focus and resolution could be applied for different countries, different means of transports or even internal logistics in a terminal or a retail warehouse. Implementation of future electrical and autonomous supply chain elements such as the Einride T-Log for wood transport could be an interesting concept for further cost and emissions evaluation with the model. The model could be rewritten in open-source software such as QGIS, using a free CRF such as Google Maps or Open Route Service, to broaden availability and use cases.

4.4 Conclusion

Based on the results of this study, several conclusions can be made:

- This study reinforces previous studies' findings concerning realistic potential to reduce GHG emissions as well as trucking costs by using larger roundwood trucks with greater net cargo weight on well-chosen routes.

- With a more generous regulatory framework without route-specific permits, larger HCT vehicles could be used in corridor clusters, reducing GHG emissions and trucking costs with less risk of ending up idle due to flow variances or shortages.

- Transports with a majority of the transport work allocated to an HCT transport on an well-chosen corridor yields reduction on GHG emissions and trucking costs. Generally, a longer corridor facilitates a bigger procurement area while a focused transport stream such as between a rail terminal and an industry allow for a shorter corridor.

- To further increase the potential of reducing GHG emissions and trucking cost, it's important to find ways to cut terminal-related costs, especially regarding terminal handling.

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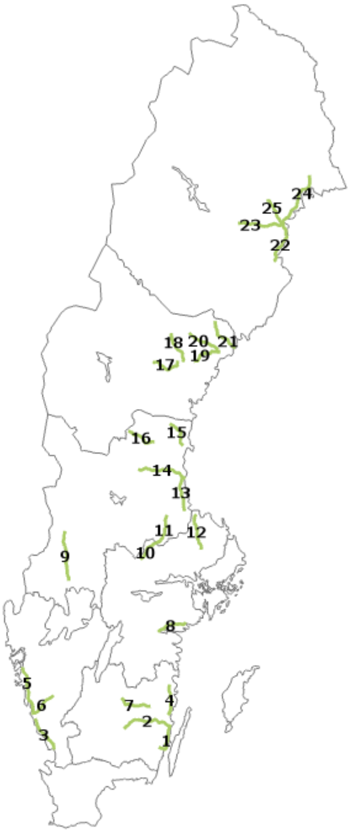
Appendix

Map and numbering of corridors



Corridor gross data tables

National area	Corri-dor ID	Corridor lenght, km	All transports (74-t) within reach of the model						
			Transport distance, km						
			Mean	Me-dian	St. Dev	Roundwood flow, kt	Diesel, kL	CO2 emission, tonnes	fuel cost, thousand €
SE21	1	56,9	67,5	65,4	30,4	1303	1389	3902	2153
	2	99,4	78,0	73,9	41,2	1741	2606	7322	4039
	4	54,4	73,5	67,3	38,3	999	1599	4494	2479
	7	62,2	46,0	43,8	27,8	1044	856	2406	1327
						5087	*6450*	*18124*	*9997*
SE23	3	64,9	70,1	63,5	36,7	977	1546	4344	2396
	5	91,0	73,4	63,5	38,9	849	1463	4111	2267
	6	52,7	66,4	65,7	29,2	1083	1635	4594	2534
						2908	*4644*	*13049*	*7198*
SE12	8	53,6	60,1	55,2	27,6	1375	2158	6063	3344
	10	50,9	61,2	57,2	31,5	1165	1909	5365	2959
	12	65,7	71,9	69,2	35,6	1658	2115	5942	3278
						4199	*6181*	*17370*	*9581*
SE31	9	92,1	68,5	63,5	36,5	1814	3355	9428	5201
	11	53,6	68,4	63,7	37,8	1621	2384	6699	3695
	13	68,4	61,6	59,5	31,3	1837	2320	6518	3596
	14	95,3	71,2	67,5	40,5	1202	2379	6686	3688
	15	53,8	64,4	62,1	31,0	1390	2613	7342	4050
	16	55,7	55,3	52,4	30,6	825	1189	3340	1842
						8689	*14240*	*40013*	*22071*
SE32	17	61,5	88,6	86,3	44,7	615	1504	4228	2332
	18	60,1	82,7	84,2	41,6	803	1834	5154	2843
	19	60,8	63,7	57,1	36,7	1307	2249	6320	3486
	20	67,9	66,4	59,5	38,5	1111	2002	5626	3104
	21	68,4	60,6	57,0	30,6	1049	1721	4836	2668
						4885	*9311*	*26165*	*14432*
SE33	22	78,3	62,1	55,5	35,4	1306	1850	5198	2867
	23	85,8	69,1	60,0	40,9	1015	1571	4413	2434
	24	115,3	70,8	60,2	43,7	1255	2110	5929	3270
	25	57,6	61,9	59,5	31,1	1062	1592	4473	2468
						4638	*7123*	*20014*	*11040*
						30406	*47948*	*134735*	*74320*

			CO2-beneficial via-corridor transports (direct 74-t and via-corridor 90-t)										
National area	Corridor ID	Corridor lenght, km	Transport distance, km			Roundwood flow, kt	Diesel, kL		CO2 emission, to		fuel cost, thousand €		terminal cost, thousand €
			Mean	Median	St. Dev		direct	v-c	direct	v-c	direct	v-c	
SE21	1	56,9	95,2	96,8	17,0	224	584	514	1640	1443	905	796	162
	2	99,4	123,8	124,5	22,5	340	1171	809	3291	2273	1815	1254	246
	4	54,4	120,8	123,2	19,0	177	601	529	1688	1487	931	820	128
	7	62,2	-	-	-	-	-		-	-	-	-	-
						741	*2355*	*1852*	*6619*	*5203*	*3651*	*2870*	*536*
SE23	3	64,9	118,8	117,6	22,3	186	620	536	1742	1506	961	831	135
	5	91,0	123,1	125,0	19,0	204	704	550	1978	1546	1091	853	148
	6	52,7	97,0	98,1	15,7	189	516	482	1451	1355	800	747	137
						580	*1840*	*1568*	*5171*	*4407*	*2852*	*2431*	*419*
SE12	8	53,6	99,3	95,0	20,6	220	606	526	1704	1479	940	816	159
	10	50,9	102,9	98,4	27,1	114	321	287	903	805	498	444	82
	12	65,7	120,5	123,5	18,2	140	474	409	1332	1149	735	634	101
						474	*1402*	*1222*	*3939*	*3433*	*2172*	*1894*	*343*
SE31	9	92,1	142,7	142,9	20,6	83	329	275	925	773	510	426	60
	11	53,6	135,3	135,5	27,9	126	475	421	1334	1184	736	653	91
	13	68,4	105,1	104,6	21,0	281	835	663	2347	1863	1294	1028	203
	14	95,3	122,0	118,1	24,9	263	887	651	2492	1829	1375	1009	190
	15	53,8	98,5	95,6	19,2	322	888	760	2495	2137	1376	1179	233
	16	55,7	88,3	84,6	18,9	65	164	134	462	377	255	208	47
						1139	*3578*	*2905*	*10055*	*8164*	*5546*	*4503*	*823*
SE32	17	61,5	145,8	151,3	20,7	106	441	388	1239	1090	684	601	77
	18	60,1	131,1	129,3	18,5	230	844	764	2372	2148	1309	1185	166
	19	60,8	124,6	127,5	21,1	168	588	508	1652	1429	911	788	121
	20	67,9	126,0	129,2	29,3	155	526	439	1479	1233	816	680	112
	21	68,4	99,7	97,5	19,8	121	328	253	922	711	509	392	87
						781	*2728*	*2353*	*7665*	*6611*	*4228*	*3647*	*564*
SE33	22	78,3	111,6	114,2	20,6	220	682	578	1918	1624	1058	896	159
	23	85,8	129,4	133,3	21,6	141	510	404	1433	1136	790	626	102
	24	115,3	145,0	144,2	21,9	172	699	501	1964	1407	1083	776	124
	25	57,6	101,7	104,4	17,3	110	322	306	904	860	499	474	80
						643	*2213*	*1789*	*6219*	*5026*	*3430*	*2773*	*465*
						4358	*14116*	*11688*	*39666*	*32844*	*21880*	*18117*	*3149*

			CO2- beneficial and cost efficient via corridor transports (direct 74-t and via-corridor 90-t)										
			Transport distance, km			Roundwood flow, kt	Diesel, kL		CO2 emission, t		fuel cost, thousand €		terminal cost, thousand €
National area	Corridor ID	Corridor lenght, km	Mean	Median	St. Dev		direct	v-c	direct	v-c	direct	v-c	
SE21	1	56,9	98,7	100,7	18,4	74	200	163	563	457	311	252	54
	2	99,4	130,3	130,4	19,8	268	972	629	2731	1766	1506	974	193
	4	54,4	154,7	155,9	8,3	4	16	14	44	39	24	21	3
	7	62,2	-	-	-	-	-		-	-	-	-	-
						345	*1188*	*805*	*3338*	*2262*	*1841*	*1248*	*250*
SE23	3	64,9	127,3	125,8	18,1	94	333	280	937	787	517	434	68
	5	91,0	129,6	130,6	18,8	126	459	324	1289	911	711	502	91
	6	52,7	89,0	89,0	0,7	0	1	1	2	1	1	1	0
						221	*793*	*605*	*2228*	*1699*	*1229*	*937*	*159*
SE12	8	53,6	113,8	110,7	19,3	69	217	184	611	517	337	285	50
	10	50,9	135,0	133,7	19,9	2	7	6	20	17	11	9	1
	12	65,7	127,5	130,3	14,5	91	326	272	915	765	505	422	66
						161	*550*	*462*	*1546*	*1299*	*853*	*716*	*117*
SE31	9	92,1	145,5	145,8	20,0	67	273	223	768	627	423	346	49
	11	53,6	141,0	139,0	25,5	87	345	298	968	837	534	461	63
	13	68,4	109,7	107,3	19,4	195	603	451	1694	1267	934	699	141
	14	95,3	128,7	126,0	23,9	194	685	460	1925	1292	1062	712	141
	15	53,8	98,7	95,6	17,4	212	572	466	1608	1310	887	722	153
	16	55,7	95,4	92,8	17,5	45	124	99	348	279	192	154	33
						801	*2601*	*1997*	*7310*	*5611*	*4032*	*3095*	*579*
SE32	17	61,5	152,0	155,0	15,8	89	382	332	1074	933	592	515	65
	18	60,1	137,4	135,4	18,1	128	490	424	1377	1192	759	657	93
	19	60,8	126,3	128,0	19,3	152	538	462	1510	1297	833	715	110
	20	67,9	129,0	130,4	26,1	102	353	280	992	786	547	433	74
	21	68,4	102,2	101,6	19,0	95	263	193	738	543	407	300	68
						566	*2025*	*1691*	*5691*	*4751*	*3139*	*2621*	*409*
SE33	22	78,3	117,9	119,5	17,8	126	417	334	1171	937	646	517	91
	23	85,8	131,3	134,0	20,5	115	421	322	1184	905	653	499	83
	24	115,3	148,3	147,8	21,5	141	586	397	1646	1117	908	616	102
	25	57,6	125,6	125,6	0,0	0	1	1	3	2	2	1	0
						382	*1425*	*1054*	*4004*	*2961*	*2209*	*1633*	*276*
						2476	*8583*	*6613*	*24118*	*18583*	*13303*	*10251*	*1789*