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A Method of Finding HCT Roundwood Corridors for Reduction of GHG Emissions and Fuel Costs in Sweden

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Abstract: Background and Objectives: in Sweden during 2016, 71.6 million metric tonnes (t) of forest biomass (roundwood and forest fuels) were 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. The objective was, therefore, 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 potential in comparison to the conventional 74 t-truck transport system for Swedish conditions. Materials and Methods: the study used data from actual roundwood transports during 2016 along with a digitalization of the Swedish road network (National Road Database, SNVDB) for corridor identification. In four steps we: (1) identified supportive networks, (2) identified flow supporting corridors on the technically supportive networks, (3) applied a calibrated route finder (CRF) to route relevant transports both directly from the landing to the receiver and via the corridor, gathering drive distance information and, for example, (4) analyzed transports fuel consumption and potential CO_2 savings. Results: 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 of CO_2 and €3.1 M in fuel costs. Conclusions: the study reinforces previous studies' findings concerning economic and environmental potential using HCT vehicles and identifies terminal establishment and management costs as a bottleneck in successful large-scale implementation of HCT corridors.

Keywords: high-capacity transportation (HCT); roundwood; routing; supply chain; logistics

1. Introduction

To reduce climate change effects caused by humans, there is a need to reduce greenhouse gas (GHG) emissions. In the Paris agreement, participating parties have pledged to keep global average temperature increase to below 2 °C of pre-industrial levels, with an additional pursuit of 1.5 °C. 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% [1]. 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 [1]. National transports account for a third of Sweden's total GHG emissions, of which 94% is due to road transports [2]. 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 [3,4]. Naturally, raw materials for forest products originate from ever-changing sources with different stock, therefore flexibility beyond the capabilities of trains are needed for these transports. Trucks 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 a range of quantities makes truck transport cheap and easy to use for short transports of forest raw materials. In 2014, Swedish forestry GHG emissions from silvicultural management, harvesting, and transport to industry amounted to about 970,000 t CO_2, of which the roundwood transport accounted for 43.8% [5]. Currently (2019), roundwood transports on Swedish 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 [6]. 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.

Asmoarp et al. [7] showed 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. HCT trucks typically carry more or higher piles of wood and occurs in Swedish roundwood transports as trucks with a 74 t or 90 t gross weight, compared to the gross weight of 60 t or 64 t in a conventional truck transport. Fuel consumption of 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% [6]. HCT trucks have extra axles to compensate for the higher gross weight, so the higher gross weight of the vehicle is divided between more axles, reducing the axle load and lowering the road wear in comparison to a lighter conventional truck with fewer axles [7]. 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 [8]. Furthermore, studies have shown small to no increased risk associated with overtaking longer vehicles on a 2 + 1 lane road [9]. 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.

Haraldsson et al. [10] 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 the National Road Database (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 [11] 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. [12] performed a systematic analysis of how the introduction of 74 t HCT would affect the environment, economy 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, 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 [13] 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 network's potential BK4 roads (see Table 1 for road class definitions). The results showed that too big share of HCT trucks (more than 12.5% of the fleet) would increase trucking costs and GHG emissions, and therefore it was important to direct HCTs to appropriate routes. Korpinen et al. [14] 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.

Svensson [15] 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 [15] 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 (roads below class BK4) 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.

Table 1. Definition of road classes in the Swedish public road network [16].

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

The majority of the roundwood truck transport work in Sweden 2016 was performed in the southern half, 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 [3]. 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 transport work performed despite the longer transport distances. The Swedish public road network is divided into four bearing capacity classes based on maximum gross weight and axle load [16] (Table 1).

With regard to the roundwood transport work, 96.1% is carried out on the public road network [3]. Roads with class BK1 and BK4 form a large majority of the public road network, about 82% and 12%, respectively [17]. 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 [18]. 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 the 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 [19]. Their structural strength simply cannot support the heavier vehicles. The Swedish Transport Administration [20] envisions all BK1 roads to be upgraded to BK4 in the future. Aside from the public road network, there is an extensive private road network vital to biomass transport. 86% of forest raw products (roundwood and forest residues) are collected at private roads [3]. The private road network is generally subsidized by the government and open for public traffic [21]. 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. Approximately 1400 of Sweden's more than 20,000 bridges are restricted for use with a 90 t vehicle set and cannot be crossed by them [10]. These are mostly located in the areas in and around the big cities 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 create varying degrees of complication for routing an HCT transport. 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. Each link is unique and carries additional information aside from its spatial attributes, such as road number, speed limit, road width, whether it is 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.

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. The objectives of this study were, therefore, 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?

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; CO_2 emissions from proposed terminals; gross weight or axle load restrictions on private roads.

2. Materials and Methods

In order to identify potential HCT corridors, the following workflow was used (Figure 1):

- Step I: Identifying a technically supportive network, i.e. the road links able to support the gross weight of a 90 t HCT vehicle.
- Step II: 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.

- Step III: Using a CRF to route relevant transports both directly from the landing to the receiver and via the corridor, gathering drive distance information.
- Step IV: Generating network properties
  - 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.

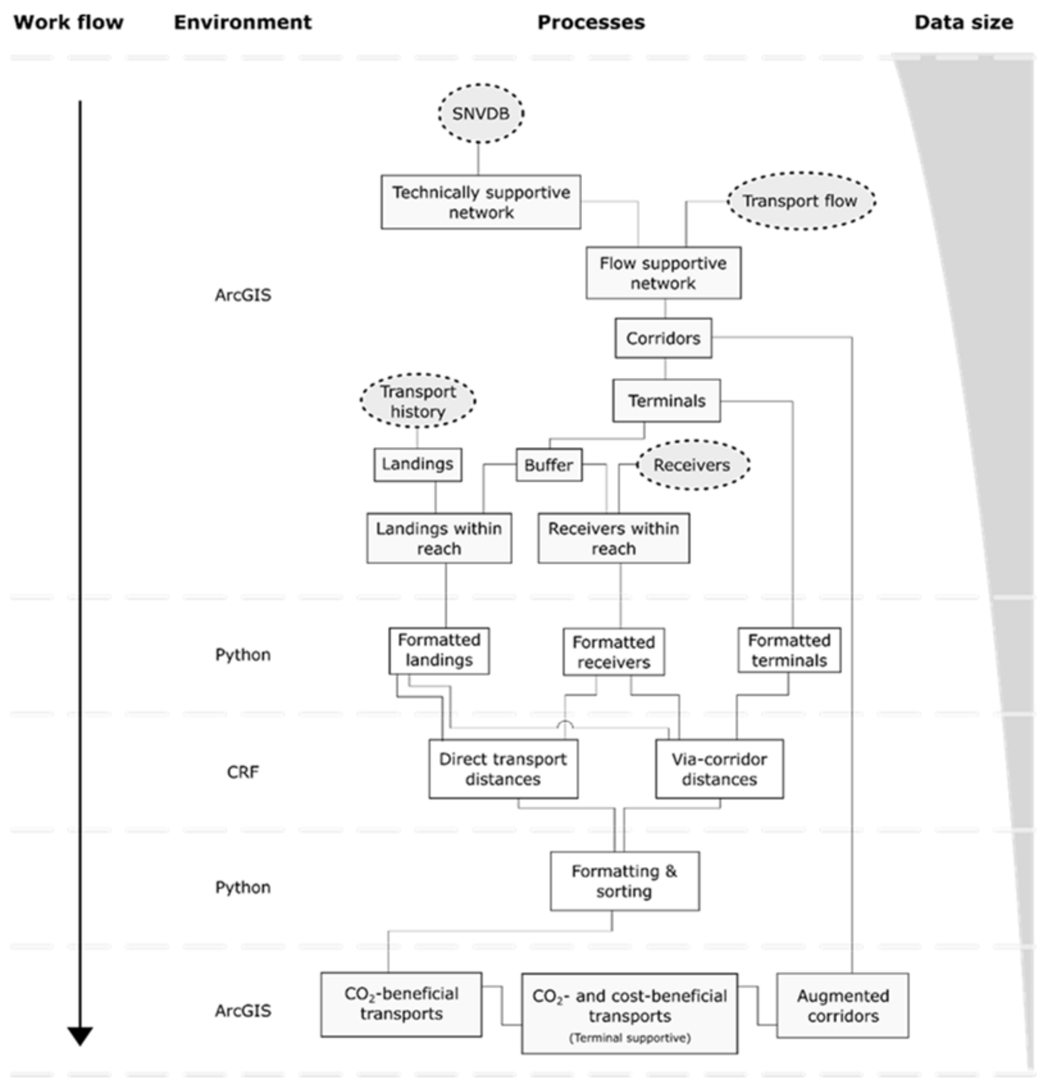


Figure 1. Schematic workflow of the study method, environment used, processes and data size. Ellipses are input data, rectangles are process-derived results.

The input dataset was 2016 transport flow data (Table 2), positions of receiving locations, and the SNVDB (Table 2). The transport data was collected by SDC and delivered by Skogforsk, and contained information about 1.34 M forest raw material transports in Sweden 2016, of which 1.28 M 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, forest fuels), transported weight and receiver ID for each transport. The dataset for receiving locations was comprised 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.

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 Type	Description
Transport flow	Line feature	Each road link's transported roundwood for 2016.
Receiving locations	Point feature	The geographic position of receiving locations.
Transport history	Table	Route information for 2016 roundwood transports.
SNVDB	Line feature	Road network with spatial and additional information, such as road class.

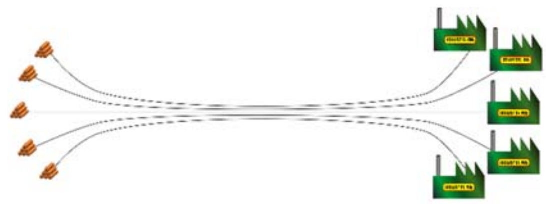
2.1. Step I: Creating a Technically Supportive Network

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. Satellite road links in the new network not able to connect to any receiving locations were removed.

2.2. Step II: Creating a Flow Supportive Network

A conventional transport flow was defined as a flow between two nodes in a transport system. These nodes could be sources or sinks, depending on the route. One example of this is a truck transport of roundwood from a small roadside deposit to an industry for processing (Figure 2). Where parallel conventional flows occur, a multiplex solution was conceptualized. The concept meant a separation of the conventional flows into three legs: i) from deposit to a terminal; ii) from one terminal to another; and iii) from the second terminal to industry. The first and last legs of transport would use conventional trucks while the middle leg would use HCT vehicles for joint transport between terminals.

a.



b.

Figure 2. (**a**) Parallel conventional transport flows; (**b**) multiplex corridor transport flow with joint high-capacity transport (HCT) between terminals.

The principle of an HCT transport system with a multiplex configuration was valid when the entire flow through one terminal node were to be received by another (Equation (1)):

$$f_{t1} = f_{t2} \tag{1}$$

where: f_1: flow at first terminal, t/year; f_{t2}: flow at second 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 multiplex HCT corridor, i.e. the route between nodes f_{t1} and f_{t2} (Figure 3), dictates the overall flow F of the corridor (Equation (2)), and was defined as:

$$F = \min(f_a, f_b, \ldots). \quad (2)$$

where: F: overall corridor flow, t/year; f_a: flow at link a, t/year; f_b: flow at link b, t/year.

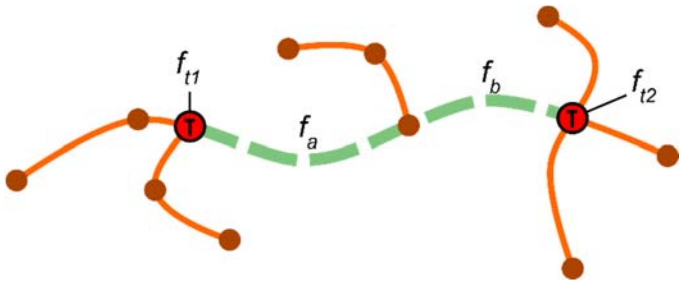


Figure 3. Schematic illustration of the road links in a multiplex HCT corridor. The green line symbolizes a potential HCT corridor between two terminal nodes. Orange lines are other links (roads) in the network, orange circles are other nodes.

A potential HCT corridor was defined as being 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 make fewer turns within a time frame making the required flow volume exponentially decaying in relation to the transport distance. The required annual roundwood flow (t) for a given distance (km) was calculated as (Equation (3)):

$$Q_a = \frac{c_c \times h_a}{h_l + \frac{d}{s_l} + h_u + \frac{d}{s_u}} \quad (3)$$

where: Q_a: Annual roundwood flow, t; c_c: Cargo capacity, t; h_a: Annual work, h; h_l: Loading time, h; h_u: Unloading time, h; 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 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 [22]; average speed of 75 km/h; terminal (loading/unloading) time of 0.5 h each. 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 (regression fit: $3E6 * \times^{-0.77}$, $R^2 = 0.9853$). The flow of the links in the technically supportive network (from step I) were compared to the cut-off function. Isolated and short segments of links (<50 km) 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.

2.3. Step III: Mining Direct and Via-Corridor Distances

Using CRF [15], transports occurring in the vicinity of each potential HCT corridor generated in step II were 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 created in Step II. 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 (proposed terminals) of the corridors was used. The selection of transports was considered being in reach of the model. A standard desktop PC with a 4 core, 4 thread 3.8 GHz clock speed Intel processor and 16 GB of RAM was used.

2.4. Step IV: Generating Network Properties

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 and Hofsten [22]. With each transport having direct and via-corridor distances (Figure 4), the fuel consumption for a 74 t direct transport (Equation (4)) was:

$$a_{74} = d_d \times q \times 0.028 \tag{4}$$

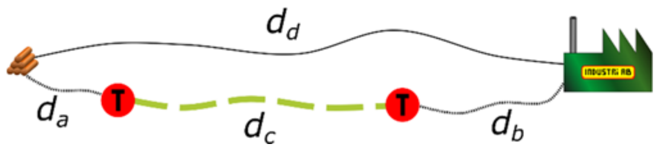


Figure 4. Schematic illustration of transport legs in a direct flow (dd) and a via-corridor multiplex flow (da+dc+db).

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 a 74-t transport to industry gates (Equation (5)):

$$a_{90} = d_a \times q \times 0.028 + d_c \times q{*}0.019 + d_b \times q \times 0.028 = q(0.028d_a + 0.019d_c + 0.028d_b, \tag{5}$$

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.

Fuel consumption was calculated for both direct and via-corridor transport for every transport in the flow supportive network. 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 CO_2 per 1 L diesel [23]. The CO_2 emission for each transport was superimposed onto the flow supportive network created in Step II. The system cost of an 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 [24]. Aside from these vehicle-specific costs, HCT corridor costs also include transport to and from terminals and terminal-related costs (Figure 5). For the conventional system, transporting directly from one point to another, the only cost item is the transport itself.

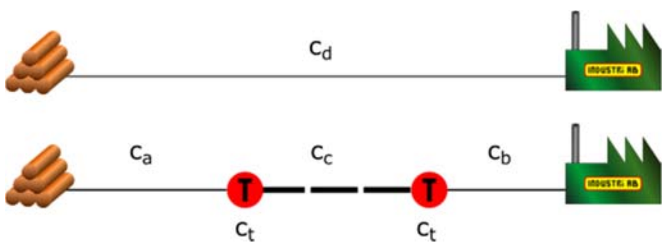


Figure 5. Cost items in a conventional (top) and HCT system (bottom).

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 (Equation (6)):

$$c_a + c_t + c_c + c_t + c_b \leq c_d \tag{6}$$

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. Transport cost for direct and via-terminal transports were calculated with the fuel consumption and a diesel price of €1.55 per L. The establishment and running costs of a new terminal are subject 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 and construction [25]. Land can be acquired through purchasing, renting or leasing. It is 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. [25] was about €1000/ha/year corrected to today's monetary value. With land acquired, construction is a cost item dependent 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 [25]. 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. [25], this study did not account for these costs. A terminal establishment as proposed in this study was a simple one. Since there would be no measuring or processing of the roundwood at these terminals, only the bare minimum of facilities would be needed. A flat gravel or asphalt surface and a wheel loader for loading the HCT vehicle would be 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 stock 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 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. [25], terminal storage capacity with piles 6 m wide, 5 m high and with 6 m passageway in between, was generalized to about 1.25 m^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 (Equation (7)):

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

where: c_{est}: terminal establishment cost, €; r_a: annual roundwood flow, m$^{3;}$ 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 [25] was used (Table 3). The tariff was based on an hourly cost of €56.64 and a productivity of 160 m^3/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 (Equation (8)) 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

The cost data for each transport were superimposed onto the flow supportive network created in Step II. The transports where both a 90 t HCT system's CO_2 emission and cost were equal or lower than those of a 74 t conventional system were then selected to form a "Step IV" terminal supportive network. This network was generalized to have the potential of being HCT corridors.

The Nomenclature of Territorial Units for Statistics (NUTS-2) system [26] was used to identify corridor distribution (Appendix A, Figure A1) in the regions of Sweden. 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. Each corridor's roundwood flow (Equation (3)) on the terminal supportive network was divided with its 90 t flow requirement (Equation (2) 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. Cluster compatibility was considered true for a corridor when at least one of its endpoints (terminals) were adjacent another corridor's endpoint. Clusters would enable corridors with insufficient flow to group and collectively utilize 90 t HCT trucks.

3. Results

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 funneling of data, the transport work accepted by the model according to the method and its restrictions decreased (Figure 6).

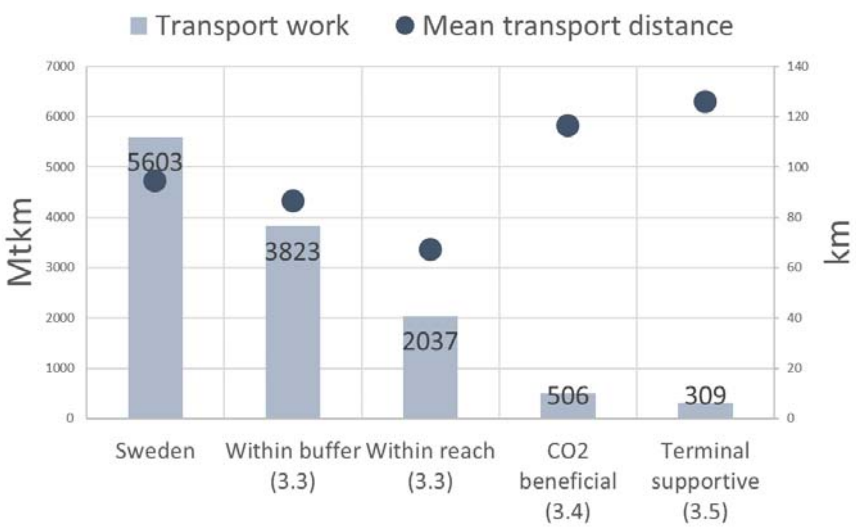


Figure 6. Transport work and mean transport distance for roundwood transport in the different stages of the study.

In the technically supportive network generated in Step I; BK1 and BK4, the two road classes defined to be able to carry a 90 t HCT truck made 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. In Step II, 25 potential multiplex HCT corridors were identified (Figure 7; Appendix A, Figure A2). 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). The mean corridor length was 69.1 km with the median being 62.2 km and the shortest and longest being 50.9 km and 115.3 km respectively (Figure 8). Total length of all corridors was 1726.3 km.

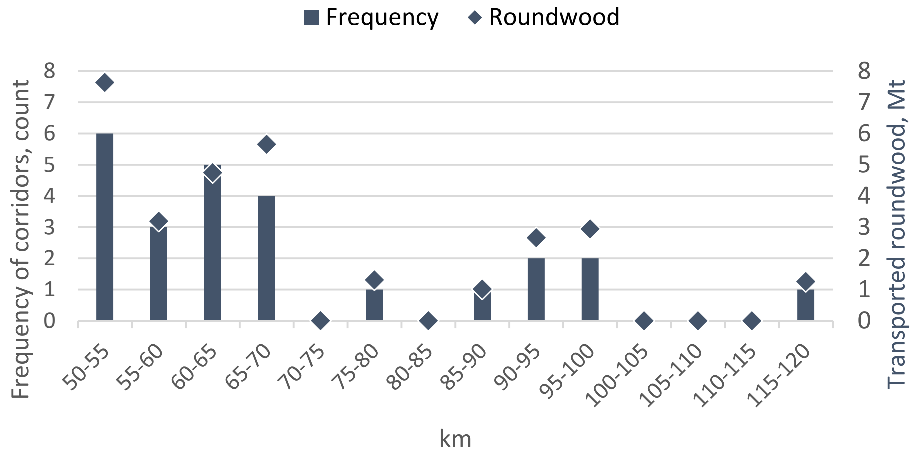


Figure 7. Frequency distribution and amount of roundwood transported (within reach of the model) by HCT corridor length. The left Y-axis is number of corridors, right Y-axis is amount of transported roundwood (Mt) and X-axis is the length of corridors (km).

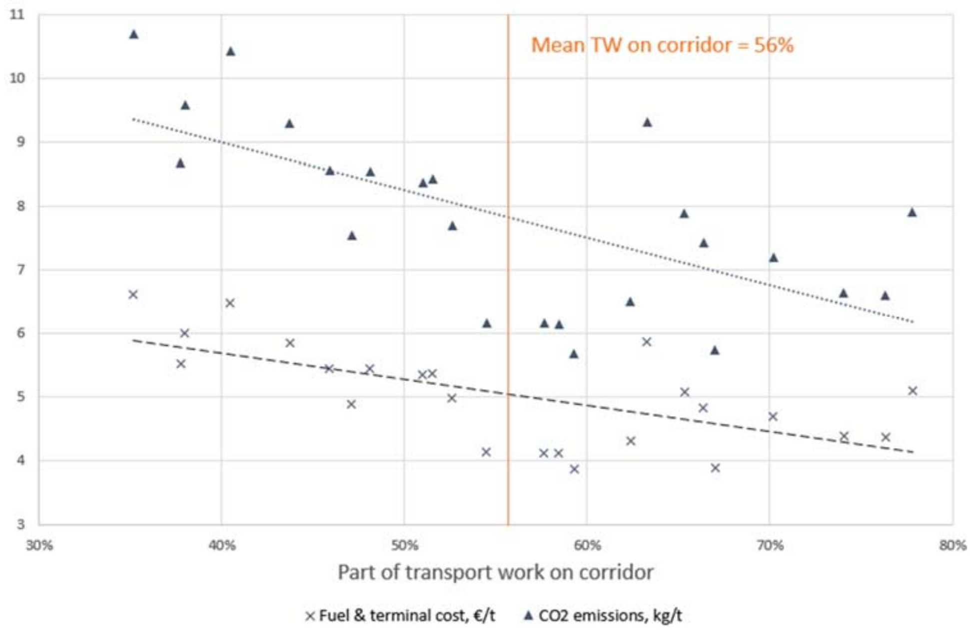


Figure 8. Identified corridor system's cost and emissions (y axis) compared to how much of the corridor system's transport work was accommodated by the HCT corridor itself (x axis).

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.For transports identified in Step II, 17.6% of transport work was found to be terminal supportive, meaning HCT corridor transport would reduce both CO_2 emissions and costs compared to conventional direct transport. Routing only these transports via corridor lowered CO_2 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 CO_2 beneficial routes with 74 t trucks. The cost of terminal handling for these transports was calculated to €1.8 M, resulting in net savings of ca. €1.3 M (Table 4).

Table 4. Potential reductions in CO_2 emissions and fuel costs (after superimposed terminal costs) for the terminal supportive via-corridor transports.

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

Basic statistics of potential savings in cost and CO_2 emissions of via-corridor transported roundwood where CO_2-beneficial and terminal supportive are presented in Table 5.

Table 5. Potential savings in kg CO_2/t and €/t for CO_2-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

Nine corridors were shown to be 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 6). 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.

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 8). 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.

Table 6. Potential 90 t HCT corridors, cluster properties, roundwood flow and approximate vehicle quantification.

Corridor ID	National Area	Potential Cluster Property	Length, 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 (3).

4. Discussion

We have created a "filtering" model to find the occurrences for where HCT corridors would be suitable for roundwood transports in terms of lowering CO_2 emissions and costs when compared to a 74 t truck system. There is no optimization in the model itself, but there is an optimization engine in the CRF used to route all transports from landing to receiver for direct and via-corridor distances. Because of this, the model is deterministic in nature and will yield a certain result based on the input. We used 74 t trucks as the reference system for comparison to the 90 t HCT trucks, even though most Swedish truck traffic is still based on a 64 t-truck system. Although 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 [22]. It also highlights future potential and could still be relevant if 74 t trucks constitute a majority of the transport fleet. However, we also assume road segments heavily used by roundwood transports between procurement areas and industries to have a small annual flow variation. 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 the 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. [14] where the terminals were already spatially set.

While generating a flow-supportive network and corridors, a minimum allowed distance of the segment (corridor) of 50 km 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, even though comparative analysis could show it having cost- and CO_2-emission saving potential. The buffer size of 50 km used in the method to find potential corridor transports was chosen due to technical restrictions in the hardware used for the modelling. Ideally this buffer size should have been bigger to capture and analyse more transports. The use of circular 50 km buffers did, however, capture about a third of total truck transport work in Sweden.

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 have produced fewer viable corridors and vice versa. 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.

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 should 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.

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 the 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 comparative 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. Most bridges restricted for 90 t vehicles are located either in the Stockholm-area or along the coast in a north-south direction [10]. The locations of the restricted bridges were classified, so there was no way to identify corridors containing one of these bridges.

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. However, this potential over-inclusion could not affect results of the overall analysis, but 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 an underestimation of potential CO_2- and cost-reduction potential in the flow network.

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 HCTs. The part of total transport work actually performed on the corridors was 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. Five zones with adjacent corridors were identified in this study, in which four 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 four 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 being 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 would not be a cost issue. One could identify a regulatory supportive network allowing empty HCT traffic just for connection of the corridors.

Fuel costs is generalized to be about a third of the total cost in transporting roundwood in Sweden [15]. 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. 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 [27], 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 CO_2 in 2010 [28].

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 wise after the event. With modification, the transport history could be switched for a transport forecast to change the application to being 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 and different means of transports. 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 evaluations with the model. The model could be rewritten in open-source software such as QGIS, using a free route finder such as Google Maps or Open Route Service, to broaden the availability and use cases.

5. Conclusions

This study reinforces previous studies' findings concerning a 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 a 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 is important to find ways to cut terminal-related costs, especially regarding terminal handling.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

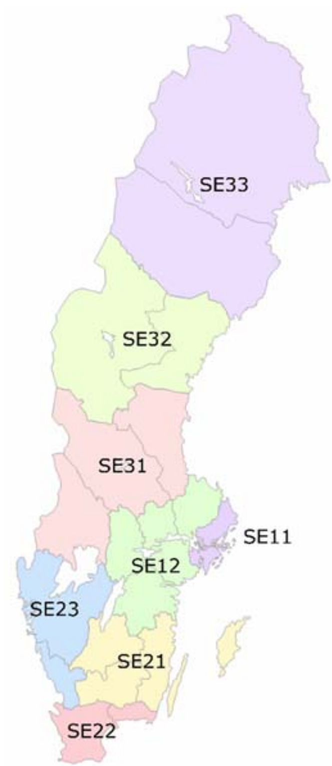

Figure A1. National areas of Sweden.

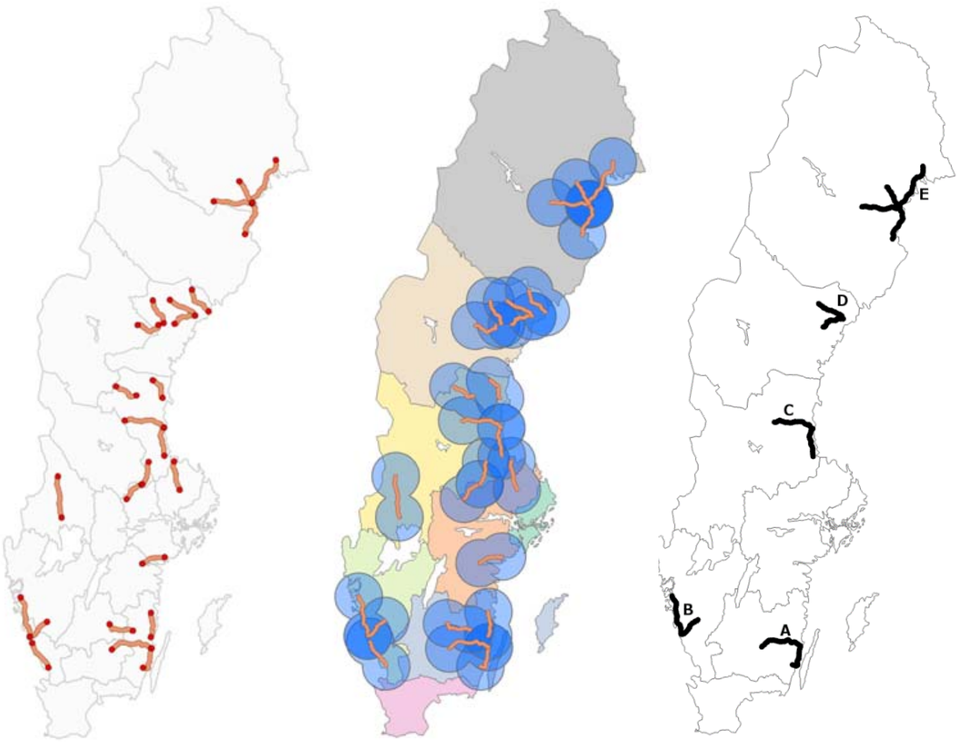

Figure A2. Left: potential HCT corridors (orange) and their connected terminals (red). Middle: buffer areas (blue) around corridor's endpoints (terminals). Right: identified clustered corridors.

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