Author(s): Kari Väätäinen, Juha Laitila, Perttu Anttila, Antti Kilpeläinen and Antti Asikainen

Title: The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators – Discrete event simulation study in case environment in Central Finland

Year: 2020

Version: Final draft

Please cite the original version:

Kari Väätäinen, Juha Laitila, Perttu Anttila, Antti Kilpeläinen & Antti Asikainen (2020) The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators – Discrete event simulation case study in Central Finland, International Journal of Forest Engineering, 31:2, 156-170, DOI: 10.1080/14942119.2020.1757324

The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators – Discrete event simulation study in case environment in Central Finland

Kari Väätäinen, Juha Laitila, Perttu Anttila, Antti Kilpeläinen and Antti Asikainen

Kari Väätäinen, Natural Resources Institute Finland, Joensuu, Finland, kari.vaatainen@luke.fi

Juha Laitila, Natural Resources Institute Finland, Joensuu, Finland

Perttu Anttila, Natural Resources Institute Finland, Joensuu, Finland

Antti Kilpeläinen, University of Eastern Finland, Joensuu, Finland

Antti Asikainen, Natural Resources Institute Finland, Joensuu, Finland

The influence of gross vehicle weight (GVW) and transport distance on timber trucking performance indicators – Discrete event simulation study in case environment in Central Finland

Today, timber trucks of gross vehicle weight (GVW) up to 76 tonne are allowed to operate on Finnish roads from roadside landings to mills. Reducing trucking costs and exhaust gas emissions have been the dominant reasons for the increased GVWs of timber trucks. A discrete-event simulation (DES) method was used to compare the impact of the truck and payload size, trucking distance and timber assortment lengths on trucking performance indicators (e.g. productivity, energy efficiency and costs of trucking) in the procurement area of a case logistic company operating in Central Finland. The studied truck sizes were 68, 76 and 84t, of which the 76-t trucks dominate timber trucking in Finland. Over a transport distance of approx. 105km with an average assortment length of 4.2m, 76-t trucks had 9% higher and 12% lower productivity (m^3/100km), 1% lower and 4% higher fuel consumption (l/m^3) and 4% lower and 6% higher trucking cost (€/m^3) compared to 68- and 84-tonner options, respectively. The improvement in regards to previous indicators was clearly bigger for the 76-tonner than the 68-tonner if the trucked wood assortments were lengthened to 5.0m. The differences in cost and fuel efficiency as well as annual trucking volumes were increased as a function of the trucking distance, when comparing the truck configurations with different GVWs and payloads. To conclude, the tendency of the size increase in GVWs in timber trucking in Finland can be justified in the light of the study results.

Keywords: Timber truck; trucking productivity; energy efficiency; trucking costs; payload; transport distance; timber logistics

Introduction

During last ten years in Finland and Sweden a lot of effort has been made to enlarge the freight capacity of timber (log) trucks (Fogdestam and Löfroth 2015; Asmoarp et al. 2018; Venäläinen and Poikela 2019) and, thus, an increase in the gross vehicle weights (GVW) has occurred. However, as the freight capacity of the vehicles has increased, comprehensive testing, follow-up and analysis of the impacts on traffic safety, roads and bridges as well as on cost- and energy efficiency (Lappi and Iikkanen 2017; Asmoarp et al. 2018; Sauna-aho et al. 2018; Venäläinen and Poikela 2019) have been carried out. The fundamental reason for the development of the increased freight capacity in timber trucking has been to control and to reduce the logistic costs of round wood taken from the forest for use in industry. In Finland, for example, the forest industry has set a development goal 2025 to boost and enhance wood supply to produce added value to the value chain while being 30% more cost-efficient within ten years (Niemelä et al. 2018).

Engine and vehicle development (incl. the enlargement of the load space) have been and will be essential in order to reach the goals of the Paris Agreement and European Commission to reduce emissions in transport sector (Paris Agreement 2015; EC 2016; 2018). Customers and forest companies are more aware of environmental impacts, thus steps towards better emission efficiency in the timber supply are being addressed by the forest industry (Palander and Kärhä 2017; Niemelä et al. 2018). Reducing the fuel consumption and traffic-related exhaust gas emissions will also have a direct impact on the entire transport economy. In addition, economies of scale and transport efficiency will be achieved with the use of larger vehicle units and greater load capacities (Asmoarp et al. 2018; Venäläinen and Poikela 2019). As the performance and load capacity of one transport unit increase, fewer vehicles and drivers are required to transport the same amount of material than earlier.

The importance of timber transportation by road is essential in the supply chain of timber from the forest to mills. For example, in Finland 76% of all timber transports from forest roads to pulp and sawmills are carried out by roughly 1,500 timber (log) trucks (Strandström 2019). Moreover, in the long-distance transportation of timber by railway and waterway, truck transport is always one part of the logistics chain before the long-distance transport methods.

Today, up to 76-t trucks in gross vehicle weight (GVW) are allowed to operate on Finnish roads. Since a legal reform allowing larger vehicles was implemented in 2013 in Finland, the use of 60-t trucks (representing the maximum GVW before the reform) has stopped and timber trucking is predominantly carried out by trucks weighing 76 tonnes and 68 tonnes GVW representing 64% and 30% shares in 2018 (Venäläinen and Poikela 2019). Earlier all timber trucks were 7-axle units representing three axles per truck and four per trailer. To increase the GVW of the 68-t trucks, a 3-axle truck and a 5-axle trailer are required, whereas a 76-t GVW unit requires a 4-axle truck and the 5-axle trailer. Comparably in Sweden, 64-t timber trucks in GVW were legally operable from 2015, and, in 2017 an act to drive 74-t trucks on predefined roads permissible for 74-tonners was initiated (Asmoarp et al. 2018).

In addition to the legally operable vehicles, so called High Capacity Transport (HCT) vehicles exceeding the country-specific limitations of maximum masses and dimensions have been operated and tested in timber trucking in especially in Finland and Sweden with special permits (Kyster-Hansen and Sjögren 2013; Asmoarp et al. 2018; Venäläinen and Poikela 2019). In Finland, 84-tonner and 104-tonner timber trucks have been driven on predefined routes over a five-year testing period, whereas in Sweden HCT-piloting has been concentrated on 74-tonner and 90-tonner timber trucks (Asmoarp et al. 2018; Venäläinen and Poikela 2019). The HCT-trucks for timber transports were predominantly focused on trucking timber from terminals to mills, however an 84-tonner was operated also from forest roads to the delivery places (i.e., terminals and mills) on predefined roads in the northern part of Finland (Venäläinen and Poikela 2019). An extension period of five years after 2018 was not approved by the Finnish Transport and Communications Agency for the 84-t timber trucks operating on low level roads.

Cut-to-length (CTL) harvesting in the Nordic countries has become more complex due to the increasing number of refined timber specifications to meet the customers' demands (Uusitalo 2005; Nurminen et al. 2006). The high number of timber assortments harvested in cuttings has resulted in wood assortment lots with low volumes at roadside landings. This, in turn increases the driving and loading times of a truck to fill the load from several supply points, and thereby reduces the timber trucking efficiency (Väkevä et al. 2000; Nurminen and Heinonen 2007; Nurminen et al. 2009; Malinen et al. 2014). In Finland, for example typically 2-10 wood assortments are harvested from thinnings and 6-16 in regeneration cuttings. The average lengths of wood assortments can often vary from 3m to 5.5m.

Due to the large variations of dimensions (i.e., length and diameter) and fresh weight densities of wood assortments over the year, it is difficult to utilize either the whole frame volume of the load space or the maximum GVW of the truck (Korpilahti and Koskinen 2012; Korpilahti 2013; Palander and Kärhä 2017). With unfavorable lengths and long stored wood assortments (i.e. drier wood), the timber load can be far less than the allowed maximum GVW. In turn, with heavy fresh densities and certain lengths of wood assortments, the maximum GVW may be reached before the frame volume of the load space. According to a large survey of timber trucking in terms of GVW, loads and trucking distances, 39% of the loads were limited by the load frame volume and the rest (61%) by the maximum vehicle weight with the 76-tonners (Palander and Kärhä 2017). Especially shorter timber lengths

(3.0-4.0m) were unfavorable for reaching the maximum vehicle weight for the 76-tonners (Palander and Kärhä 2017).

In the 21st century, follow up studies to explore the influence aspects such as operational, vehicle specific and road specific factors on trucking performance, timing and/or fuel consumption of the prevailing and dominant truck fleet have been carried out by Väkevä et al. (2000), Nurminen and Heinonen (2007), Holzleitner et al. (2011) and Klvač et al. (2013), for example. Joint results of long-term follow up studies concentrating merely on comparing legally operable trucks and HCT-trucks running with special permits have been presented, e.g., by Fogdestam and Löfroth (2015), Asmoarp et al. (2018) and Venäläinen and Poikela (2019). Moreover, the variability and controllability of a truck's GVW by aiming to achieve full payloads and effective timber trucking have been studied, e.g., by Ian et al. (2004), Brown and Ghaffariyan (2016), Trzcinski et al. (2013), Hamsley et al. (2007), Palander and Kärhä (2017).

Ghaffariyan et al. (2018) carried out a review of timber truck fuel consumption studies and compiled fuel consumption models as a function of trucks' payload; an increment of the payload by 190% increased fuel consumption per 100 kilometer of roughly 160%. Comparably, the fuel consumption per transported tonne-kilometer (t-km) will slightly decrease with an increased payload, which can be converted from the formulas by Ghaffariyan et al. (2018). According to the results of follow-up studies comparing conventional truck-trailer units to HCT-trucks in Finland and Sweden, larger trucks with higher payloads and a higher GVW resulted in even up to 20% lower fuel consumption per t-km (Fogdestam and Löfroth 2015; Asmoarp et al. 2018; Venäläinen and Poikela 2019). In addition to the payload and GVW of the truck, multiple other variables have an impact on the fuel consumption of timber trucks such as aerodynamics, as well as the driving distance and speed, road geometry, surface roughness of the road, driving behavior and vehicle properties (e.g. Klvač et al. 2013; Karlsson et al. 2015; Walnum and Simonsen 2015; Svenson and Fjeld 2016; Asmoarp et al. 2018; Venäläinen and Poikela 2019).

System analysis studies regarding purely timber trucking or timber supply logistics with timber trucking have been studied using different research methods. More specifically, Nurminen et al. (2009) introduced an activity-based costing (ABC) management system for calculating the supply costs of each wood assortment for cutting, forest transport and road transport by timber trucks. Korpinen et al. (2019) studied the efficient use of transshipment terminals and HCT trucks when supplying pulpwood in Southeast Finland by using a dynamic simulation with an agent-based modeling (ABM) approach. Vehicle routing and /or the scheduling of timber trucks have been studied by Murphy (2003), Palmgren et al. (2004), Gronalt and Hirsch (2007), Andersson et al. (2008), Flisberg et al. (2009), Oberscheider et al. (2013) and Acuna and Sessions (2014) using mixed integer programming with some variations in the approaches to searching for optimal solutions (e.g., Tabu-search, near-exact solution).

After the implementation of the legislation on larger vehicle masses and heights in Finland at the end of 2013, the understanding of the efficient use of most used truck sizes in GVW (i.e. 68 and 76-tonners) has developed from practice and from studies in Finland (e.g. Ojala 2015; Palander and Kärhä 2017). However, studying the performances of truck sizes in similar and comparable trucking conditions in practice is time consuming and/or expensive to set up and complete. Thus, a dynamic simulation method with a discrete-event simulation (DES) approach was selected for this study to compare the impact of truck and payload size, trucking distance and timber assortment lengths on trucking performance. 68-t and 76-t truck-trailer units, which predominantly operate from forest landings to end-use places and terminals in Finland, were the truck sizes of interest. As a theoretical reference, the performance of an 84-t GVW truck-trailer unit was simulated and compared. The study case environment, located in Central Finland, represented fairly challenging logistic conditions with a high number of wood assortments to be delivered to several delivery places and relatively short distances.

The objectives of the study were to clarify the impact of the timber truck size, payload, driving distance and lengths of wood assortments on indicators of trucking performance using the DES method. Performance indicators of interest included the annual trucking volume in cubic meters, productivity in cubic meters per 100km of driven distance, trucking costs per transported cubic meter of timber, and the fuel consumption efficiency in liters per cubic meter of timber.

Materials and Methods

Modelling the system environment

Introduction to the timber trucking simulation model

The DES method using WITNESS simulation software integrated with Excel-based parameter input was used to model the system environment and to conduct simulations of the determined study scenarios. The first version of the timber trucking simulation model was compiled and presented by Annevelink et al. (2017) and model updates were carried out to better match the operating environment and the simulation scenarios of interest in this study.

The simulation model consists of a predetermined operating area with roadside landings, a road network, delivery places and timber trucks hauling timber from the roadside landings to delivery places. The trucks are operated according to the timber demand and fulfil the supply of each delivery place at a given time. The timber demand for each delivery place was defined by using the 2016 historical timber supply data from the trucking company where timber was hauled on a year-round basis when timber became available for hauling. However, timber transports to meet the timber demand may be changed depending on the system boundaries and constraints. The set of constraints influencing the timber trucking logistics by the highest demand included i) the amount of transported timber assortment at a simulation time versus the demand of each assortment on a monthly level, ii) the maximum number of arrivals of each truck per shift to the delivery place, iii) the daily opening hours of timber receptions of delivery places, iv) transportable volumes of timber assortments at road side landings and v) the maximum storage times of timber assortments at roadside landings.

In addition to the main trucking logistics, the running of timber trucks in the model are controlled by the work shifts of drivers, statutory and work specific breaks, time consumption and driving speed formulas for timber trucking in Finland (Nurminen and Heinonen 2007), as well as the driving distances and specifications for timber loading and unloading.

Operation environment specifications

The operation environment of the studied system was located in Central Finland (Figure 1). The timber trucking logistics of the simulation system were constructed to match the logistics of a timber supply operator transporting timber from roadside landings to delivery places in the procurement area. Specifications for the trucking logistics were discussed with the transport manager of a trucking company. In total 12 delivery places were entered into the system environment; 8 sawmills, 2 pulp mills and 2 train terminals. Each delivery place had a number of timber assortments and volumes on a monthly level to be supplied by the trucking operator. In Figure 2 the supply volumes of the timber assortments are presented. In the simulations, four timber trucks were defined to transport the timber to the delivery places.

Roadside (RS) landings of timber for the simulation were artificially generated by sorting logging sites from the large historical data sets of the sites from timber purchasing companies operating in the study area. The initial logging site data included removals in volume and log wood-pulpwood ratios of each tree species, the location in co-ordinates, the average stem size of each tree species and the finishing date recording of the logging. The selection of logging sites for the study from the initial logging site data was determined so, that i) selected sites were within the typical supply area of the timber trucking company and, ii) the sites' wood species and sawn wood-pulpwood ratio fulfilled the timber assortment distribution to meet the delivery places' demand for one year. After the selection of the logging sites to be used in the simulations as data for the RS landings, timber assortments and volumes were determined by the site-specific information on the tree species' sawn wood-pulpwood ratios and the RS landing location in relation to the locations of each delivery place. Short distances were weighted when determining timber assortments and their delivery places to each RS landing.

The average size of the RS landings was 410m³ with a range of 30–1,597m³. The size corresponded well the typical landing size (i.e., logging site removal) variation in Central Finland. The number of timber assortments at the RS landings varied from 2 to 12 and resulted in 9 as an average. The minimum volume of each assortment was set to 10m³. The timber demand of each delivery place was defined by utilizing the history data of the timber supply from the trucking company representing 2016. Road network data by DigiRoad (Digiroad 2018) and a road network analysis in ArcGIS were used to calculate the shortest road distances from thee RS landings to delivery places. Road distances from the RS landings to the timber destinations varied from 2 to 235km averaging 85km.

Control of simulation runs of one year

Timber trucks had timber cranes attached all the time during the simulation run, which is typical in the practical timber trucking case area, mostly due to the short driving distances. In addition, all the hauling cycles of the timber were carried out from the RS landings and hauled directly to the delivery places, thus no intermediate storage was used. Weekly operations followed consisted of two working shifts (i.e. day and night shifts) so that Saturday afternoon and whole Sunday were off-shift. A holiday period was set for the whole of July.

At the start of the simulation run, the RS landings were read from the base data for all of the RS landings into the adaptive RS landing matrix including volumes of wood assortments, co-ordinates and the driving distances from the RS landings to the delivery places. The base data included the RS landings in a chronological order following the registered finishing time of the timber logging for each site. The maximum size of the adaptive RS landing matrix was set to 80 RS landings and the matrix was updated with new RS landings two times per week in chronological order (i.e. emptied landings were replaced by the next ones from the base data). An adaptive RS landing matrix with a varying timber volume corresponded to the harvesting production of the logging fleet supplying timber for truck transports in the timber supply area. In the scenario simulations, the same order of RS landings was followed. The selection of the landings and truck routing was conducted by the volume and location information for the RS landings' timber assortments in the adaptive RS landing matrix.

For each simulation scenario, the monthly demands for the timber assortments for each delivery place were rescaled to match the annual performance of each truck type with the same number of working hours (Figure 2). Thus, each truck type had the same number of working days, but the transported volumes differed between truck types. The delivery shares of timber assortments were kept the same for the different truck types.

Selection rule for the delivery place, timber assortment and RS landing in each hauling cycle

In the timber trucking simulation model, the delivery place, timber assortment and RS landing are selected by the predefined ruling for each trucking cycle. In the selection ruling, the timber assortment with the highest demand in volume was prioritized. The highest timber demand in a particular simulation time was determined by the amount of transported timber assortment versus the demand for each assortment to each delivery place within a particular month. However, if any of the defined constraints were active, the timber assortment and the delivery place could change. The set of constraints influencing the ruling of timber trucking included i) the maximum number of arrivals of each truck per shift to the delivery place, ii) the daily opening hours of the delivery place's timber reception, iii) the available timber volume of each assortment at each RS landing, and iv) the maximum storage time of timber assortments at roadside landings. Moreover, in order to emphasize truck-specific operating areas, each truck had unique weighing coefficients [0-1] for each wood assortment while determining the highest timber demand in the simulation time. Once the RS landing was selected for the truck as a source for timber hauling, the RS landing was reserved only for that truck until the time the truck had been loaded and had left from the RS landing location. Thus, reserved RS landings cannot be selected by other trucks.

A maximum arrival for the specific truck in one shift was set to two arrivals per specific delivery place. Timber receptions of pulp wood receiving facilities (pulp mills and train terminals) were open day and night (4 delivery places), whereas the opening times of the sawmills' timber receptions varied between 6:00-16:00 and 6:00-22:00. One sawmill had exceptional opening times and their timber reception was open day and night. The maximum storage time for sawn wood assortments was set as fixed to 40 days and pulp wood assortments for 50 days. If the storage time of a timber assortment exceeded these maximum storage times, there was a 7-day time window to select the roadside landing for trucking the timber to delivery place. During these days, 70km was set as the maximum road distance for each truck to select the RS landing location for the operations. After exceeding the time window, the first truck selecting for the upcoming hauling route had to fulfill this constraint.

If none of the constraints were limiting, the next RS landing was selected by the delivery place and a timber assortment with the highest demand at that moment. If the delivery place was other than the place where the truck was leaving from, backhauling occurred (Figure 3). The simulation logic selected the RS landing location with the shortest distance from the current truck location. By that means, the routing enabled the RS landings to be selected with a long hauling distance to the delivery place of the call, hence resulting in shorter hauling cycles compared to hauling cycles which would start from and return to the same place.

If the delivery place of the call was set to be the same as the place of the previous delivery, the selection of the site followed the closest available RS landing with the shortest road distance. If the site was located further than 70km by road, the wood assortment and delivery place with the second highest timber demand was selected. While defining and selecting the RS landing matching the call, the RS landings which contained at minimum a full truck-trailer load volume of the called assortment or assortments at the same delivery place, were preferred. If “full load RS landings” were not available, a combination of RS landings to fill the load space was determined using the shortest road distance approach. The logic of the RS landing and wood assortment selection for the truck is shown in Figure 4.

Hauling cycle of a timber truck

A simulation run of the timber trucking started from a predefined truck park with a fixed location at start of the morning shift by driving a truck unloaded to a pre-appointed RS landing. According to the rules for the timber trucking logistics, the proper RS landing was selected from the adaptive RS landing matrix. For the loading and unloading times of single and multiple assortments, a combination of time element parameters by Nurminen and Heinonen (2007) and modified parameters were used (Table 1 and Table 2). Some of the parameter values were estimations by the researchers reviewed and approved by a person involved in timber trucking operations. In addition, trucking speed formulas for driving empty, driving loaded and driving between RS landings were taken from the study by Nurminen and Heinonen (2007).

If the timber assortment at the RS landing was not enough to fill the load space, and the landing contained an assortment or assortments with the same delivery place as the called assortment had, loading was continued by filling the rest of the free load space with these assortments. If the load space was not filled up at the RS landing, an additional landing was selected using the shortest distance approach and, thus the truck would drive between RS landing sites. However, if the size of the load was no more than 4m^3 smaller than the calculated load capacity for the timber, the truck started driving as loaded from the RS landing to the delivery place.

Eight-axle, nine-axle and ten-axle timber tucks with 68t, 76t and 84t of respective GVWs were selected for simulating trucking scenarios (Figure 5). The timber assortment specific load capacity was calculated for each of truck-trailer type. The average fresh weight density of each timber assortment for the winter (average values from South Finland) (Table 3), the load space dimensions of the truck and the trailer, loading density of the timber assortment and the mass limitations for the truck and the trailer were used in the capacity calculations (Korpilahti 2013, Korpilahti and Koskinen 2013) (Table 4). For all truck types, the cross-sectional area of carrier's load space was 6.93m^2 and for the trailer 7.16m^2, respectively. The lengths of load spaces for the 68, 76 and 84-tonners were 6.7m, 7.2m and 9.1m respectively for the carriers and 10.2m for the trailers. In all loads, the timber crane of the truck was included in the load capacity calculation. The average total vehicle masses for the 68 and 76-tonners corresponded closely to the masses of the follow-up studies by Näsärö and Korpilahti (2015) and Palander and Kärhä (2017), in which the average fresh weight densities during the winter were used in the simulations. In this study an 84-tonner has been selected as a comparable scenario.

According to the load size calculation for each of the truck type configurations, variations in the load size and vehicle's total mass when loaded were relatively large within timber assortments (Table 5). Trucks' GVWs were allowed to exceed by two tonnes at max., while determining the load size for each timber assortment and truck type.

After arriving at the delivery place, an additional delay time expressed in minutes was determined by a theoretical distribution (*Triangle*: mean 10; min. 8; max. 15) (see Table 2). The delay time included scaling of the trucking unit and a short waiting before the unloading. Unloading was always carried out using the timber crane of the truck-trailer unit and the timing of the unloading was calculated with the parameters presented in Table 1. A separate delay time for minor repairs, maintenance and refueling was included in a theoretical distribution (*LogNormal*: mean 7.83; SD 17). Before the start of the next load cycle, a new RS landing was selected from the adaptive RS landing matrix using the timber trucking by demand rule. On occasions, when the weekday was a Wednesday or Saturday and the daytime work shift was about to end (with less than one hour of time remaining), the truck-trailer unit was directed to a truck park either from the delivery place or from the loading place to make a shift change. This procedure took into account additional (i.e., uncompensated) driving in all scenarios. In all other cases, the shift change was conducted at the beginning or the end of the route where the truck was at the time of the shift change. For each work shift, the durations of break-times (incl. meal, coffee and statutory breaks) and shift changes were determined using the normal distributions: break-time: *Normal*(mean

45min, SD 2min), shift change time: *Normal*(mean 18min, SD 2min). In the simulation run, break-time occurred once roughly in the middle of the work shift and shift change time at the end of the work shift. In Figure 6, the logic of the timber trucking is illustrated.

Simulation scenarios and calculation of energy efficiency and costs

Two main scenario-sets were made for the simulation scenarios; a scenario-set of road distances for a business as usual-case and a scenario-set of timber truck types. In all distance scenarios, scenarios for all three truck types were defined. In the business as usual (BAU) scenarios the road distances corresponded to the distances from the analysis of digital road-data. Three additional distance-scenarios were determined; BAUdist-15km, BAUdist+15km, BAUdist+30km (Table 6). To test the influence of the carrier weight for the 84-tonner, one scenario simulation was carried out in BAU conditions. In addition, the influence of the timber length on the result indicators for the 68 and the 76-t trucks were studied by comparing two timber length scenarios with average lengths of 4.2 and 5.0 meters. Thus, in total 15 scenarios were simulated and analyzed. A straightforward method was used to calculate the road distances for the additional distance-scenarios: a distance increase or decrease was calculated from the initial values of the BAU’s road distances between roadside landings and delivery places at 15km intervals. However, the distances between roadside landings were kept the same in all scenarios.

Each of the simulation scenarios was replicated five times to confirm the accepted level of variation in the results of the scenario runs. Average values and 95% confidence level values were expressed for the productivity values, whereas only average values were shown for the other results. For each simulation scenario the trucking performance indicators were shown (i.e., the annual timber trucking volume, driving efficiency in cubic meters per 100km, energy efficiency in liters per cubic meter and the cost efficiency in euros per cubic meter).

The fuel consumption values were acquired from the Finnish Transport and Logistics SKAL organization and Metsäteho Ltd. (Table 7).

The cost accounting format followed conventional Finnish cost accounting standards for road transport vehicles (Ajoneuvojen… 2009). The purchase prices of each truck carrier type and trailer were acquired from truck and trailer dealers in 2016 and other cost factors and values were converted from the values received from the organization Finnish transport and logistics SKAL. However, all the cost factor values were scaled to match the price level in March 2018 using cost indexes from Statistics Finland. The values for the cost calculations are presented in Table 7.

Results

Operational data

The average trip distance of one hauling cycle varied from 132km to 138km for the vehicle types in the BAU scenario. Due to the larger load space of the 76- and 84-t trucks, the trip distance or average transport distances were longer than for the 68-tonner (Table 8 and Figure 7). The larger the vehicle type and the load was, the smaller the share of single source loads were (i.e., more multisource loads at different RS landings) and thus, the longer driving distance between RS landings to fill the load was (Table 8).

The average total weights of the trucks were 98.7%, 94.2% and 93.7% of the GVW for the 68, 76 and 84-tonners, respectively. Compared to a 68-t truck, the volumetric size of the average load was 8.0% higher for a 76-t truck and 23.9% higher for an 84-t truck (Table 2). The differences in the operating hour productivity and the driving performance in m^3/100km were more moderate. The 76-tonner had 5.2% and 7.4% and, 84-tonner had 14.0% and 19.7% higher values than the 68-tonner (Table 8). In the comparison of the energy efficiency of timber trucking in liters per transported m^3 of timber, the 84-tonner had 2% lower fuel consumption than the 68-tonner had.

The most time-consuming work element was driving the tucks when loaded, representing 24-26% in the BAU scenario and 28-30% in BAU+30km scenario (Figure 8). The larger the vehicle unit was the lower the share of driving loaded and unloaded were, and the larger the share of the loading, unloading and driving between decks were. Alternatively, when comparing the work element consumptions for one load cycle, the vehicle types differed from each other in loading, unloading and driving between piles, while diving empty and driving loaded were about the same.

Annual trucking volumes

The 84-tonner trucked 11.6–15.8% more timber in one year compared to the 68-tonner in comparable annual working hours (Figure 9, Table 9). The respective figures were 6.8–9.1% while comparing the 84-tonner and the 76-tonner. The 76-tonner had a 4.5–6.2% better annual trucking performance than the 68-tonner had. The performance difference increased as the driving distance increased. The influence of a distance decrease of 15km of the road distance was a 7.5-10.3% increase in the annual trucking performance depending on the vehicle type and distance.

Driving, energy and cost efficiency

The 84-tonner reacted most positively to the longer distances in terms of the driving efficiency in m^3/100km and energy efficiency in l/m^3 compared to smaller vehicle types (Table 9). At distances of BAU+30km, which corresponded to a hauling cycle of 195-198km, the 68-tonner and 76-tonner had 18.9% and 11.0% lower driving efficiency and, 5.1% and 4.1% higher fuel consumption in liters per 100km compared to the 84-tonner, in respective order.

Regarding the unit costs for each trucked m^3 of timber, the smallest differences between the vehicle types were in the shortest distance scenario (BAU-15km); the 68-tonner was 6.4% and the 76-tonner was 4.3% more expensive than the 84-tonner (Figure 10). In the BAU+30km scenario the differences were 10.1% and 6.4%, respectively. Respective comparisons of the 76-tonner and other truck types are presented in Table 10.

Timber lengths and RS landing volumes

If the average timber length of each assortment was lengthened to 5 meters from the BAU scenario averaging 4.2m in length, the influence on the trucking performance was distinctly larger for 76-t vehicle than for the 68-t vehicle (Table 11). The average vehicle mass increased by just 1.9% for the 68-t vehicle, whereas the 76-t vehicle's mass increased by 4%. Moreover, the load size increased by 6.7% for the 76-tonner and only 3.1% for the 68-tonner. Due to the improved filling of load space for the 76-tonner, the annual trucking volume also increased more for the 76-tonner than the 68-tonner. Additionally, the trucking cost was 4.2% lower for the 76-t truck compared to the 68-tonner in the BAU scenario with a five-meter wood assortment length.

To evaluate operational conditions of the simulation scenarios, timber volumes of the RS landings were recorded once per week from each simulation (Table 12). Neither the average nor the SD values of the RS landing volumes differed much while comparing scenarios. For example, distinctly smaller RS landing volume levels would have increased difficulties in trucking by increasing the share of driving between the RS landings and the landing selections with longer driving distances. On average, 10,000m^3 of an RS landings' timber volume corresponded to the amount which could be trucked in 17 working shifts using 68-t trucks (with 4 trucks) in the BAU scenario, whereas 84-t trucks can transport the corresponding timber volume in 15 working shifts (i.e. in one and a half weeks).

Discussion

Timber trucking simulations were carried out using a discrete-event simulation model constructed for the study. Test and pre-simulation runs, with visualization of the timber trucking in a map presentation, and by using time element diagrams, distribution histograms of the variables of interest and changes in the adaptive RS landing matrix ensured the verification of the simulation model.

Some aspects need to be emphasized for a discussion of the model validation when comparing the model assumptions, input-output transformations and accuracy of the outputs to a real system. No intermediate storage was included in the simulations and all timber was trucked from the RS landings straight to the delivery places (mills and train terminals). In practice, in the late winter, a large share of the trucking capacity is directed to transport timber from the RS landings with poorer road connections to intermediate terminals next to roads with good trafficability. In addition, some truck drivers have working patterns which involve loading of several wood assortments with smaller volumes from RS landing to empty the storage and transporting mixed-timber load to the closest timber terminal, wherefrom one assortment loads are trucked to mill. In turn, this leads to additional loading and unloading of timber compared to a working pattern with direct trucking from RS landing to mill.

Of the operating area, the RS landings with the most unfavorable locations related to the delivery places were often neglected in the selection of the upcoming load cycle. This was due to the procedure for finding the closest available RS landing for the targeted timber. Thus, most often the timber of these RS landings was transported at the end of the maximum timber storage time. Comparably in practice, depending on the road condition or if there is high demand for certain saw log assortment, for example, the assortments are quite often transported from the RS landings within a short time frame.

Due to the lack of time studies and/or follow-up data for the truck sizes of interest, the same work element functions and functions of trucking speeds were used for all truck sizes. The functions used were from the study by Nurminen and Heinonen (2007), which consisted of 60-t truck-trailer units. The drivers, who have had experience with 60-tonners and the 76-tonners, have speculated that the driving speeds on lower level roads decreased with full loads of 76 tonnes in GVW mainly due to the higher loads and swaying of the vehicle unit on uneven roads. In addition, loading has been estimated to be more time consuming per unit than for the previous GVW due to the necessity for higher precision while adjusting the grapple load into the load space to reach as high a filling rate as possible (i.e., as close to the GVW of the truck as possible). In this respect, in the simulations the time consumption formulas for these time elements of the hauling cycle may result in slight underestimations. On the other hand, unloading the timber was always carried out by the timber loader, which overestimates the time for unloading especially compared to unloading the timber using wheel loaders or material handling machines at mill yards. Moreover, the simulation did not include extra time which occurs on a daily basis due to adjusting the driving to match the mills' time windows for truck arrivals in practice. While discussing the trucking performances of different GVWs, it must be emphasized that 84 tonners are not operating anymore from RS landings in Finland. With a special permit, a few 84 tonner trucks are operating from terminals to pulp and saw mills on predetermined routes.

The operational environment in the BAU scenarios resulted in relatively short load cycle distances and thus short trucking distances when loaded. In Finland, the average trucking distance from the roadside landing to the mill was 105km in 2018 (Strandström 2019). Thereby, scenario results of the BAU+30km corresponded better to the statistics and results of other studies. Fuel efficiency calculations (l/m^3) were rough approximates due to the use of fixed fuel consumption values for each truck type. In studies by Venäläinen and

Poikela (2019) and Klvač et al. (2013) the increased driving distance had a decreasing effect on fuel consumption. The reasons for the reduced fuel consumption as the distance increases are the reduced proportion of crane use and the increased share of better roads. Recently, for the 76-tonner and the 84-tonner, fuel consumption curves as a function of the driving distance have been presented by Venäläinen and Poikela (2019). Comparable formulas for the 68-tonner were not available. To compare the correspondence of the 68- and 76-tonner payloads and total weights with the follow-up study results by Palander and Kärhä (2016), the payloads were roughly one tonne smaller and the total weights were two to three tonnes smaller than in the study by Palander and Kärhä (2016). The values by Palander and Kärhä (2016) included a timber loader and its weight, thus the results were comparable to these simulation results.

Depending on the season, location, tree species and the combination of the cutting date of the timber and the storage time, the fresh weight density of pulp wood can vary up to 100kg/m³, according to the Lindblad and Repola (2019). Thereby, instead of fixed fresh weight densities for timber assortments, as used in this study, varying fresh weight densities throughout the year may have impacted the results and comparisons between the truck types. Particularly, the 68-tonner and the 84-tonner would have had a larger load increase in volume than the 76-tonner if summer weight densities would have been used. Difficulties in reaching the maximum GVW of the 76-tonner was due to the short timber lengths and light timber as Palander and Kärhä (2017) also found. Either trucking longer wood assortments with the current truck specifications or constructing 76-tonner tractors with longer load space would increase the load capacity and thus, improve the trucking performance of 76-tonners compared to the 68-tonner.

While comparing the proportion of multi-sourced loads, in the follow-up study by Nurminen and Heinonen (2007) for a 60-t truck-trailer unit the proportion was 38% of all loads, and in our study only a bit higher (41-44%) for the 68-t and 76-t trucks. In addition, the average driving distance between RS landings was 13.9km in Nurminen and Heinonen (2007) and 26km in Väkevä et al. (2000), whereas in this simulation study it was 27-28km for the 68- and 76-tonners. Moreover, the share of single assortment loads (77% for the 68-tonner) was somewhat similar in our study compared to the share in Nurminen and Heinonen (2007) (84%). Thereby, the load cycle routing indicators, presented above, verify the simulation and validate the results in this context.

With the 76-tonner and the transport distance of 105km (BAU+30km), the trucking cost was identical (7.6€/m³) with the average timber trucking cost in Finland 2018 (Strandström 2019). In cost calculations by Venäläinen and Poikela (2019) for the 76-tonner the annual trucking performance was 67,500m³, whereas for a comparable transport distance (105km; BAU+30km) it was roughly 64,000m³ in the current simulations. Venäläinen and Poikela (2019) calculated a 7.5% cost saving with an 84-tonner compared to a 76-tonner for a 100km distance. In respective comparison, the cost saving was 6.4% in our study.

The differences in energy efficiency between the vehicle types were small in the BAU scenario due to the short trucking distances and higher share of other work than just driving. In the BAU+30km scenarios, the 84-tonner consumed 4% less fuel per m³ of timber than the 76-tonner at a driving distance of roughly 105km. Respectively, Venäläinen and Poikela (2019) calculated roughly a 10% fuel saving. Fuel consumption per cubic meter over a 100km distance was about the same for the 76-tonner in Venäläinen and Poikela (2019) than in our study. However, for the 84-tonner, the monitored fuel consumption in Venäläinen and Poikela (2019) resulted in a lower average fuel consumption per 100km than the value used in our simulations. In addition to this, another influencing factor on the differences was the volume of the payload used in the calculations. The timber lengths of the trucked wood assortments in our study resulted in low filling rates especially for the 76-tonner and the 84-tonner trucks as could be seen in Table 8.

DES modelling proved its applicability to compile a complex study environment and to conduct a dynamic system analysis of the timber trucking logistics. Further use of the model would help us to make more sensitivity analysis of the variables of interest in identical operational environments. More specifically, a more detailed analysis of the impact of the fresh weight density and timber assortment length variations on trucking performance for different vehicle combinations should still be carried out.

The tendency of the size increase in GVWs in timber trucking in Finland can be justified in the light of the study results. The best option was 84-t timber truck due to the distinctly longer load space and bigger payload of the truck (i.e. prime mover) when compared to trucks of lighter GVWs. However, compared to 68- and 76-tonners, few meters longer and several tonnes heavier vehicle unit of 84-tonner may have more difficulties to operate in forest roads with limited trafficability and more restrictions to pass bridges with weight limits. Moreover, we have to bear in mind that currently 84-t timber truck is not allowed on road network in Finland due to permissible maximum weight of 76 tonnes.

To conclude, the same trend was identified in this study as in earlier studies. In terms of cost and fuel efficiency as well as annual trucking volumes, by the use of heavier GVWs and bigger payloads in timber trucking the benefit increases as a function of the distance compared to truck configurations with lower GVWs and payloads (e.g., Laitila et al. 2016; Asmoarp et al. 2018; Prinz et al. 2018; Venäläinen and Poikela 2019). These findings concerning the use of heavier GVWs in timber transports promote the national and international goals to reduce exhaust emissions per transported volumes, to decrease the truck density on roads and to ease the shortage of drivers for trucking timber in the future.

Acknowledgements

This study received contributions from the FORBIO (3500010200) and Smartlog projects. The first development of the timber trucking model was conducted in the S2Biom-project. The funding was from the EU and Strategic Research Council of the Academy of Finland.

References

Acuna M, Sessions J. 2014. A simulated annealing algorithm to solve the log-truck scheduling problem. In: Simulated Annealing: Strategies, Potential Uses and Advantages. NOVA Science:191–220.

Ajoneuvojen kustannuslaskennan perusteet [Basics of vehicle cost accounting]. 2009. Suomen Kuljetus ja Logistiikka SKAL ry. 13p. Finnish.

Andersson G, Flisberg P, Lidén B, Rönnqvist M. 2008. RUTTOPT : a decision support system for routing of logging trucks. Canadian Journal of Forest Research 38:1784–1796.

Annevelink B, Anttila P, Väätäinen K, Gabrielle B, Garcia-Galindo D, Leduc S, Staritsky I. 2017. Chapter 4 - Modeling Biomass Logistics. In. Panoutsou C, editor. Modeling and Optimization of Biomass Supply Chains. Top Down and Bottom Up Assessment for Agricultural, Forest and Waste Feedstock; p. 79–103.

Asmoarp V, Enström J, Bergqvist M, von Hofsten H. 2018. Effectivare transport på väg – Slutrapport för project ETT 2014-2016. [Improving Transport Efficiency – Final Report of the ETT 2014-2016 Project]. Skogforsk, Arbetsrapport 962, 65 p.

Brown M, Ghaffariyan MR. 2016. Timber Truck Payload Management with Different In-Forest Weighing Strategies in Australia. Croatian Journal of Forest Engineering 37(1):131–138.

Digiroad. 2018. Digiroad - National Road and Street Database. https://www.liikennevirasto.fi/web/en/open-data/digiroad#.W-Ey69UzZEY

EC (European Commission). 2016. A European Strategy for Low-Emission Mobility. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. https://eur-lex.europa.eu/resource.html?uri=cellar:e44d3c21-531e-11e6-89bd-01aa75ed71a1.0002.02/DOC_1&format=PDF

EC (European Commission). 2018. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. 25 p.

Flisberg P, Lidén B, Rönnqvist M. 2009. A hybrid method based on linear programming and tabu search for routing logging trucks. Comput. Operations Res. 36(4):1122–1144.

Fogdestam N, Löfroth C. 2015. Slutrapport, demonstration av ETT- och ST-fordon 2011–2013. [ETT-demo, demonstration of ETT- and ST-vehicles]. Skogforsk, Arbetsrapport 872, 40 p.

Ghaffariyan M, Barrier C, Brown M, Kuehmaier M, Acuna M. 2018. A short review of timber truck fuel consumption studies. Industry Bulletin 21. Afora. 6 p.

Gronalt M, Hirsch P. 2007. Log-truck scheduling with a tabu search strategy. In: Doerner, K.F., Gendreau, M., Greistorfer, P., Gutjahr, W.J., Hartl, R.F., Reimann, M, editors. Metaheuristics – Progress in Complex Systems Optimization. New York: Springer, p. 65–88.

Hamsley AK, Greene WD, Siry JP, Mendell BC. 2007. Improving Timber Trucking Performance by Reducing Variability of Log Truck Weights. Southern Journal of Applied Forestry 31(1):12–16.

Heinonen T. 2016. High Capacity Transport -ajoneuvoyhdistelmien vaikutukset liikennevirtaan [Influence of High Capacity Transport vehicles on traffic]. Diplomityö. Aalto Yliopisto. 134 p.

Holzleitner F, Kanzian C, Stampfer K. 2011. Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager. Eur J Forest Res (2011) 130:293–301.

Ian PC, Greene WD, Clutter ML. 2004. The Impact of Mill Policy to Discourage Overweight Log Trucks. Southern Journal of Applied Forestry 28(3):132–136.

Karlsson M, Gårdhagen R, Ekman P, Söderblom D, Löfroth C. 2015. Aerodynamics of Timber Trucks - A Wind Tunnel Investigation; SAE Technical Paper; No. 2015-01-1562; SAE International: Warrendale, PA, USA.

Klvač R, Kolařík J, Volná M, Drápela K. 2013. Fuel Consumption in Timber Haulage. Croatian Journal of Forest Engineering 2013 34(2):229–240.

Korpilahti A, Koskinen OH. 2012. Puutavaran autokuljetus tehokkaammaksi [More transport efficiency to timber trucking]. Metsätehon tuloskalvosarja 1/2012. Finnish.

Korpilahti, A. 2013. Puutavara-autot mitta- ja massamuutosten jälkeen [Timber trucks after the upgrade of GVW's and heights]. Metsätehon tuloskalvosarja 11/2013. Finnish.

Korpinen O-J, Aalto M, Venäläinen P, Ranta T. 2019. Impacts of a High-Capacity Truck Transportation System on the Economy and Traffic Intensity of Pulpwood Supply in Southeast Finland. Croat. j. for. eng. 40(1):89–105.

Kyster-Hansen H, Sjögren J. 2016. Swedish Roadmap for High Capacity Transport (HCT). In: Blanquart C, Clausen U, Jacob B, editors. Towards Innovative Freight and Logistics, Volume 2:89–104.

Laitila J, Asikainen A, Ranta T. 2016. Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass and Bioenergy. 90: 252–261.

Lappi T, Iikkanen P. 2017. HCT-ajoneuvojen liikennejärjestelmävaikutukset [HCT vehicles' influence on transport systems]. Liikenneviraston tutkimuksia ja selvityksiä 57/2017. Liikennevirasto. 37 p. Finnish.

Lindblad J, Repola J. 2019. Mänty- ja koivukuitupuun tuoretiheys paino-otantamittauksessa ja tuoretiheyden mallinnus varastointiajan perusteella [Fresh weight density of pine and birch pulpwood by weight sampling measurement and modeling of fresh weight density by storage time]. Metsätieteen aikakauskirja 2019-10101. Tutkimusartikkeli. 26 p. Finnish.

Malinen J, Nousiainen J, Palojärvi K, Palander T. 2014. Prospects and Challenges of Timber Trucking in a Changing Operational Environment in Finland. Croatian Journal of Forest Engineering. 35(1):91–100.

Murphy G. 2003. Reducing trucks on the road through optimal route scheduling and shared log transport services. South. J. Appl. For. 27(3):198–205.

Näsärö, O-P, Korpilahti A. 2015. Puutavarayhdistelmien akselimassat ja kuormatilan koko [Axle masses and load space dimensions of timber trucks]. Metsätehon tuloskalvosarja 9/2015. Finnish.

Niemelä T, Hämäläinen J, Kärhä K, Pajuoja H, Pirinen H, Siekkinen A, Väkevä J. 2018. Efficient wood supply 2025 (Update 2018). Metsäteho Ltd. 20 p.

Nurminen, T, Heinonen J. 2007. Characteristics and time consumption of timber trucking in Finland. Silva Fennica 41(3):471–487.

Nurminen, T, Korpunen H, Uusitalo J. 2009. Applying the activity-based costing to cut-to-length timber harvesting and trucking. Silva Fennica 43(5):847–870.

Oberscheider M, Zazgornik J, Henriksen CB, Gronalt M, Hirsch P. 2013. Minimizing driving times and greenhouse gas emissions in timber transport with a near-exact solution approach. Scandinavian Journal of Forest Research 28(5):493–506.

Ojala J. 2015. Kustannus- ja kannattavuusvertailu 68- ja 76 –tonnisten ajoneuvoyhdistelmien välillä [Cost and economy comparison of 68- and 76-t trucks]. Satakunnan ammattikorkeakoulu. Logistiikan koulutusohjelma. 26 p. Finnish.

Palander T, Kärhä K. 2017. Potential Traffic Levels after Increasing the Maximum Vehicle Weight in Environmentally Efficient Transportation System: The Case of Finland, J. sustain. dev. energy water environ. syst. 5(3):417–429.

Palmgren M, Rönnqvist M, Varbrand P. 2004. A near-exact method for solving the log-truck scheduling problem. International Transactions of Operations Research 11(4):447–464.

Paris Agreement. 2015. United Nations 2015. 25 p. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Prinz R, Väätäinen K, Laitila J, Sikanen L, Asikainen A. 2018. Analysis of energy efficiency of forest chip supply systems using discrete-event simulation. Applied Energy. 235:1369–1380.

Sauna-aho J, Koskinen OH, Sauna-aho P, Rivanti T. 2018. HCT- ja normaaliajoneuvojen energiankäyttö, hiilidioksidipäästöt ja tiekuormitus [HCT and normal vehicles energy use, CO_2 emissions and road wear]. Liikenneviraston tutkimuksia ja selvityksiä 51/2018. Liikennevirasto. 65 p. Finnish.

SKAL. 2018. [Cost calculation for the 76-t truck-trailer unit for timber transport]. Finnish transport and logistics SKAL. 08/2018. Excel-spreadsheet. Finnish.

Strandström M. 2019. Puunkorjuu ja kaukokuljetus vuonna 2018 [Timber harvesting and transport 2018]. Metsätehon tuloskalvosarja 17a/2019. 32 p. Finnish.

Svenson G, Fjeld D. 2016. The impact of road geometry and surface roughness on fuel consumption of logging trucks, Scandinavian Journal of Forest Research. 31(5):526–536.

Trzciński G, Sieniawski W, Moskalik T. 2013. Effects of Timber Loads on Gross Vehicle Weight. Folia Forestalia Polonica, series A. 55(4):159–167.

Uusitalo J. 2005. A framework for CTL method-based wood procurement logistics. International Journal of Forest Engineering. 16(2):37–46.

Väkevä J, Lindroos J, Rajamäki J, Uusi-Pantti K. 2000. Puutavaran keräilyajon ajanmenekki [Time consumption of driving between decks by timber trucks]. Metsäteho Report 96. 24 p. Finnish.

Venäläinen P, Poikela A. 2019. Puutavara- ja hakeajoneuvojen massojen noston vaikutukset [Influence of increased GVW’s on timber trucks and chip trucks]. Metsätehon raportti 253. 56 p. Finnish.

Walnum HJ, Simonsen M. 2015. Does driving behavior matter? An analysis of fuel consumption data from heavy-duty trucks. Transportation Research Part D: Transport and Evironment. 36:107–120.

Table 1. The time parameters used for loading and unloading timber truck for each handled m^3 of timber. All unloading was carried out using the truck's own timber crane.

Single assortments	Loading, min/m^3	Unloading, min/m^3
sawn wood	0.44 [1]	0.34 [2]
pulpwood (long)	0.74 [1&2]	0.6 [2]
pulpwood (short)	1.05 [1&2]	1 [2]
energy wood	1.2 [2]	1.2 [2]
Multiple assortments	Loading, min/m^3	Unloading, min/m^3
2 assortments (sawn wood) [2]	0.54	0.44
3 assortments (sawn wood) [2]	0.64	0.54
4 assortments (sawn wood) [2]	0.74	0.64
2 assortments (pulp wood) [2]	0.94	0.74
3 assortments (pulp wood) [2]	1.04	0.84

[1] Nurminen and Heinonen (2007), [2] expert estimations, [1&2] Updated value from Nurminen and Heinonen (2007) and expert estimation

Table 2. Auxiliary times during loading and unloading.

Auxiliary time during loading	Time duration
single-sourced loads [1], min/RS storage	11.25
multi-source loads [1], min/RS storage	6.52
Delay time during loading	Time duration
By lognormal distribution (mean [1], SD [2]), min/load	7.83, 17
Auxiliary time during unloading	Time duration
By triangular distribution [2] (mean, min, max), min/load	10, 8, 15

[1] Nurminen and Heinonen (2007), [2] expert estimations

Table 3. Wood assortment specifications including the assortment type, fresh weight density, loading density, average log length and number of bundles in a carrier and a trailer.

Wood assortment type	No. of assortments	Fresh weight density [1], kg/m^3	Loading density [1], %	Log lengths [2], m	No. of bundles in carrier; 68t, 76t, 84t	No. of bundles in trailer
Pine saw log	6	850-870	68-69	4.3-4.6	1, 1, 1-2	2
Spruce saw log	5	790	68-69	4.3-4.6	1, 1, 1-2	2
Birch saw log	2	860-900	60-66	3.4	2	3
Pine small sized log	3	930	62-63	4.3-5.0	1, 1, 1-2	2
Spruce small sized log	2	845	62	4.3-5.0	1, 1, 1-2	2
Pine pulpwood	2	950	61	4.3	1, 1, 1-2	2
Spruce pulpwood	1	865	61	4.3	1, 1, 1-2	2
Birch pulpwood	3	910	52-54	3.0-5.0	1-2, 1-2, 1-3	2-3
Energywood	1	600	46	5.0	1, 1, 1-2	2
Total	25					

[1] Korpilahti (2013), Korpilahti & Koskinen (2013)

Table 4. Vehicles' tare masses, payloads and total masses with the load for the truck and the trailer.

Vehicle masses	68-t truck	76-t truck	84-t truck
Carrier mass, kg	12,000	13,000	13,000/14,000*
Trailer mass, kg	7,800	7,800	7,800
Loader mass, kg	3,500	3,500	3,500
Vehicle tare mass, kg	23,300	24,300	24,300/25,300*
Max. payload of carrier, kg	12,500	18,500	24,500/25,500*
Max. payload of trailer, kg	34,200	34,200	34,200
Max. total mass of carrier, kg	28,000	35,000	42,000
Max. total mass of trailer, kg	42,000	42,000	42,000

*84-t truck has one axle more than 76-t, but smaller cabin thus two scenarios were taken into account

Table 5. The average, range and variation values for the calculated load spaces for all timber assortments and the total masses for each vehicle type.

	Load size, m^3				Total mass, t			
Truck type	Average	*min*	*max*	*SD*	Average	*min*	*max*	*SD*
68-t truck	52.5	*43.1*	*59.1*	*4.4*	68.2	*52.6*	*70* [1]	*3.9*
76-t truck	57.2	*43.4*	*65.3*	*5.9*	73.2	*53.6*	*77.0*	*5.4*
84-t truck	64.1	*48.9*	*74.8*	*5.7*	79.2	*53.6*	*84.0*	*6.3*

[1] two tonnes of over mass was allowed in determining the load size

Table 6. Simulation scenarios used in the study.

Scenario set 1; distance	Scenario set 2; truck type	Abbreviation	Definition
BAU-scenario	68-t	BAU_68t	68-t trucks with original road distances and 4.2m timber lengths in average
	76-t	BAU_76t	76-t trucks with original road distances and 4.2m timber lengths in average
	84-t	BAU_84t	84-t trucks with original road distances and 4.2m timber lengths in average
	84-t HC	*84t_HC*	*84-t trucks with one tonne heavier carrier (HC) than BAU_84t and 4.2m of timber lengths*
	68-t LT	*68t_LT*	*68-t trucks with 5.0m of timber lengths*
	76-t LT	*76t_LT*	*76-t trucks with 5.0m of timber lengths*
BAU-15km	68-t	BAU-15km_68t	68-t trucks with 15 km shorter road distances compared to BAU
	76-t	BAU-15km_76t	76-t trucks with 15 km shorter road distances compared to BAU
	84-t	BAU-15km_84t	84-t trucks with 15 km shorter road distances compared to BAU
BAU+15km	68-t	BAU+15km_68t	68-t trucks with 15 km longer road distances compared to BAU
	76-t	BAU+15km_76t	76-t trucks with 15 km longer road distances compared to BAU
	84-t	BAU+15km_84t	84-t trucks with 15 km longer road distances compared to BAU
BAU+30km	68-t	BAU+30km_68t	68-t trucks with 30 km longer road distances compared to BAU
	76-t	BAU+30km_76t	76-t trucks with 30km longer road distances compared to BAU
	84-t	BAU+30km_84t	84-t trucks with 30 km longer road distances compared to BAU

Table 7. Cost accounting factors and the values used for calculating trucking costs for the truck types of the study.

Cost factors	*68-t truck*	*76-t truck*	*84-t truck*
Fixed cost and capital factors			
Truck (carrier), €	155,000	175,000	190,000
Trailer, €	79,000	79,000	79,000
Equipment, €	40,000	40,000	40,000
Crane + cabin, €	73,500	73,500	73,500
Number of truck wheels	10	12	14
Truck wheels, €/piece	650	650	650
Number of trailer wheels	20	20	20
Trailer wheels, €/piece	350	350	350
Vehicle price (tyres not included), €	*334,000*	*352,700*	*366,400*
Interest rate, %	3	3	3
Annual value loss, % (carrier&crane , trailer)	20 , 25	20 , 25	20 , 25
Insurance, €/year	9,000	10,000	11,000
Traffic costs, €/year	1,660	1,660	1,660
Administration costs, €/year	6,000	6,000	6,000
Maintenance costs, €/year	4,000	4,000	4,000
Uncompensated driving, €/year	2,000	2,000	2,000
Lifetime factors			
Truck lifetime, years	5	5	5
Trailer lifetime, years	5	5	5
Max distance for tyres, km	120,000	120,000	120,000
Salary factors			
Driver salary, €/h	18	18	18
Indirect salary, %	68	68	68
Variable cost factors			
Fuel price, €/l	1.07	1.07	1.07
Fuel consumption, l/100km	58	63	68
Lubricants cost, €/year	2,000	2,000	2,000
Repair/service, €/year	26,000	28,000	30,000
Tyres (coating), €/tyre	300	300	300
Entrepreneurial risk, margin percent, %	5	5	5

Table 8. Operational data for the BAU scenarios for all truck types (75-79 km of average transport distance). 95%-confidence intervals are expressed in *italics* in the performance data.

Data for average hauling cycle	68-t truck	76-t truck	84-t truck[1]	*84-t truck*[2]
Trip duration, h	4.23	4.33	4.60	*4.59*
Trip distance, km	132.2	132.7	136.9	*137.8*
Load size, m^3	51.3	55.4	63.6	*62.7*
Vehicle mass (loaded), t	67.4	71.9	78.9	*79.1*
Driving speed, km/h	55.1	54.9	54.8	*54.9*
Performance data				
Driving performance, m^3/100km	38.9 , *0.40*	41.8 , *0.39*	46.5 , *0.59*	*45.6 ,* 0.38
Productivity[3], m^3/h	13.3 , *0.09*	14.0 , *0.09*	15.2 , *0.12*	*15.0 ,* 0.08
Annual driving, km	187,558 , *1062*	182,219 , *1066*	178,843 , *1067*	*180,439 ,* 968
Annual trucked volume, m^3	72,761 , *391*	76,038 , *433*	83,083 , *714*	*82,032 ,* 497
Fuel efficiency data				
Fuel consumption, l/100km	58.0	63.0	68.0	*68.0*
Fuel consumption, l/m^3	1.495	1.510	1.464	*1.496*
Truck load data				
Share of single source loads, %	58.5	56.2	52.8	*53.4*
Share of single assortment loads , %	78.6	77.2	75.0	*75.4*
Share of full loads, %	91.9	91.7	91.0	*90.8*
Avg. distance travelled to collect a load [4], km	27.1 , *0.54*	27.6 , *0.90*	30.1 , *1.26*	*30.2 ,* 0.98

[1] lighter carrier for 84-t unit; 13,000 kg

[2] heavier carrier for 84-t unit; 14,000 kg

[3] productivity in operating hour - breaks exluded

[4] driven road distance between two or more RS storages to fill the load space

Table 9. Driving and energy efficiency figures for the vehicle types and distance scenarios. Differences in %-values are the comparisons to respective scenario of the 76-tonner.

	Driving efficency, m³/100km			
Truck type	BAU-15km	BAU	BAU+15km	BAU+30km
68-t truck	49.2 , *-6.8%*	38.89 , *-6.9%*	31.5 , *-7.2%*	26.1 , *-8.9%*
76-t truck	52.8	41.8	33.9	28.6
84-t truck	57.8 , *9.4%*	46.5 , *11.4%*	38.0 , *12.1%*	32.2 , *12.3%*
	Energy efficency, l/m³			
Truck type	BAU-15km	BAU	BAU+15km	BAU+30km
68-t truck	1.18 , *-1.2%*	1.49 , *-1.1%*	1.84 , *-0.7%*	2.22 , *1.0%*
76-t truck	1.19	1.51	1.86	2.12
84-t truck	1.18 , *-1.3%*	1.46 , *-3.1%*	1.79 , *-3.7%*	2.11 , *-3.9%*

Table 10. Timber trucking costs and comparable hauling cycle distances for the vehicle types in four distance scenarios. The differences in %-values are comparisons to the respective scenario for the 76-tonner.

	Timber trucking costs, €/m^3			
Truck type	BAU-15km	BAU	BAU+15km	BAU+30km
68-t truck	5.23 *, 2.0%*	6.07 , *2.1%*	6.97 , *2.3%*	7.89 , *3.5%*
76-t truck	5.13	5.94	6.81	7.62
84-t truck	4.92 , *-4.2%*	5.60 , *-5.7%*	6.40 , *-5.9%*	7.16 , *-6.0%*

Table 11. Dimension and performance data for 68-t and 76-t trucks for two average timber lengths of 4.2m *(equal to the BAU scenario)* and 5.0m. Differences in the %-values are comparisons to scenario for the 76-tonner and a timber length of 4.2m.

	Vehicle size and average timber length			
Performance indicators	68-t, 4.2m	68-t, 5m	76-t, 4.2m	76-t, 5m
Total vehicle mass, t	67.4 , *-6.3%*	*68.7 , -4.5%*	71.9	*74.8,* 4.0%
Avg load size of timber, m^3	51.3 , *-7.4%*	*52.9 , -4.5%*	55.4	*59.1,* 6.7%
Trucking volume, m^3/year	72,761 , *-4.3%*	74,113 , *-2.5%*	76,038	79,415 , *4.4%*
Fuel consumption, l/m^3	1.50 , *-1.0%*	*1.456 , -3.6%*	1.51	*1.432 , -5.1%*
Trucking cost, €/m^3	6.07 , *2.2%*	5.94 , *0.0%*	5.94	5.69 , *-4.2%*

Table 12. Descriptive statistics for the RS landing volumes within a simulation year in each scenario.

	Average weekly volume of RS storages in year, m³			
Truck type	BAU-15km	BAU	BAU+15km	BAU+30km
68-t truck	10,809	11,010	10,500	9,752
76-t truck	10,882	10,876	10,832	10,489
84-t truck	11,072	11,127	10,838	10,934

	Deviation of RS storages' weekly volumes in year, m³			
Truck type	BAU-15km	BAU	BAU+15km	BAU+30km
68-t truck	2,242	1,950	2,188	2,048
76-t truck	2,269	2,116	2,048	1,890
84-t truck	2,907	1,992	1,770	1,887

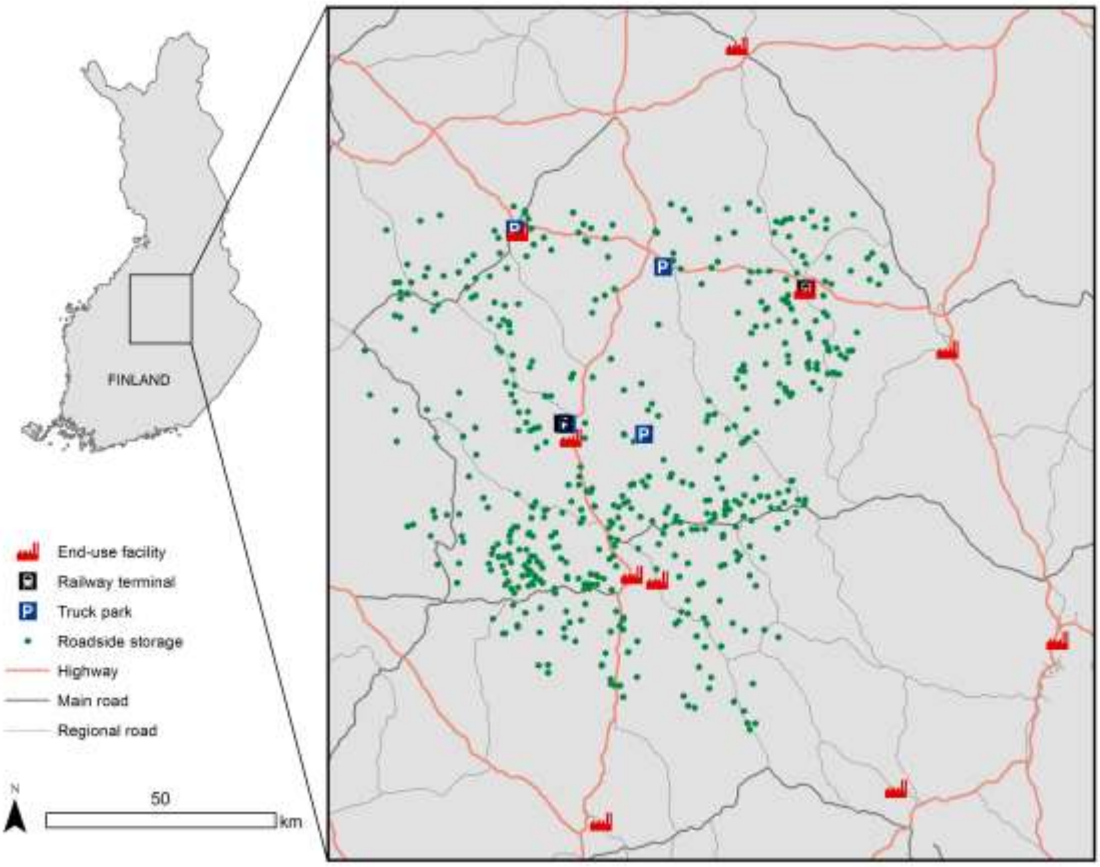

Figure 1. Operating environment of the timber trucking simulations showing the locations of roadside landings of timber, timber delivery places (end-use facilities and railway terminals), parking places of 4 timber trucks and a network of public roads.

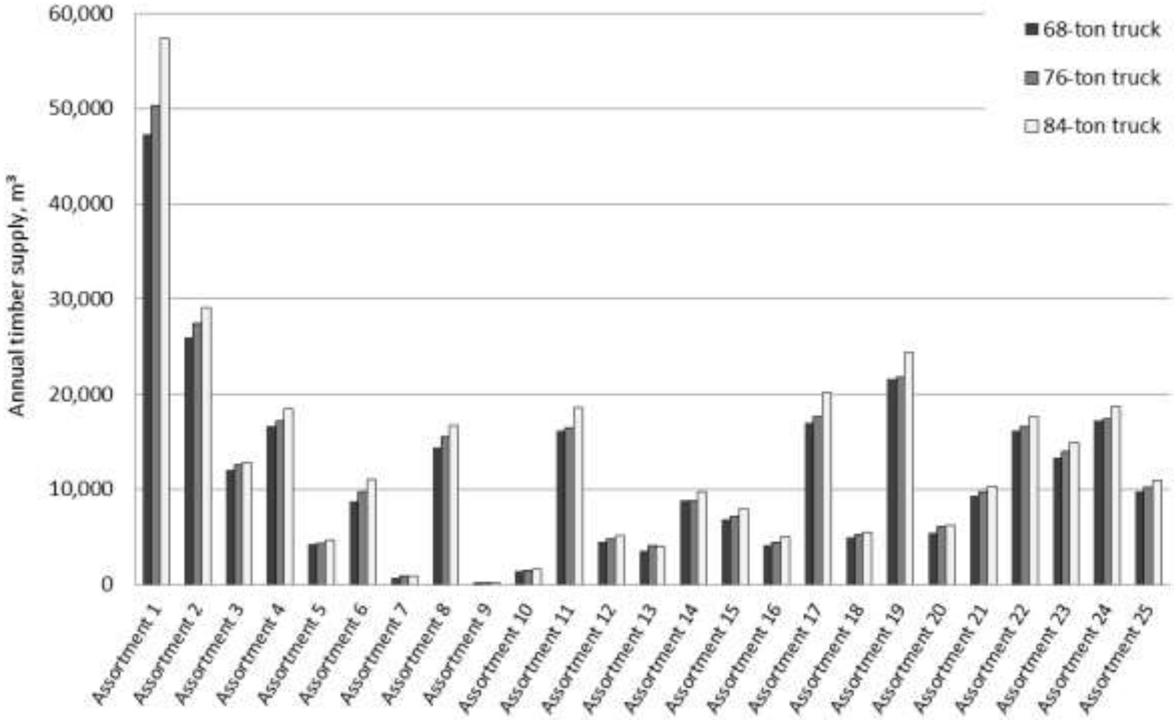

Figure 2. Annual timber supply of each wood assortment for each timber truck type in BAU-scenarios.

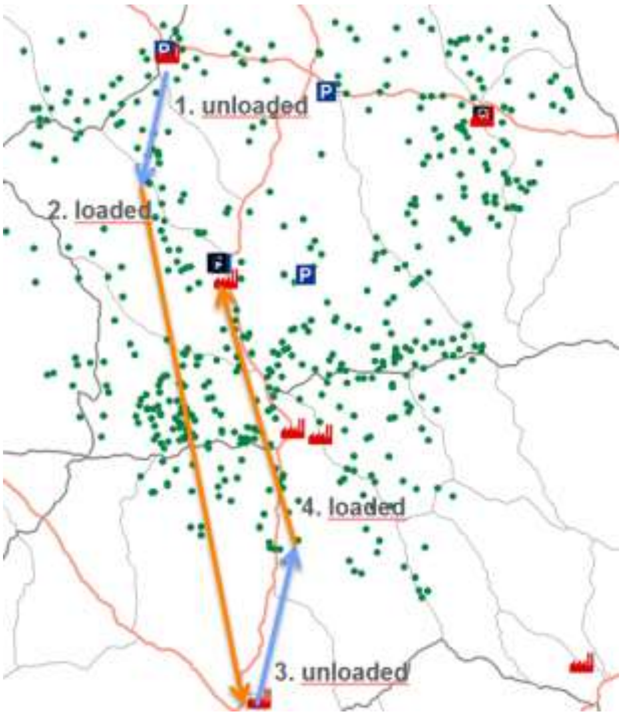

Figure 3. An illustration showing how the backhauling in the timber trucking simulation model was determined. Blue colored arrow represents driving as unloaded and orange driving as loaded.

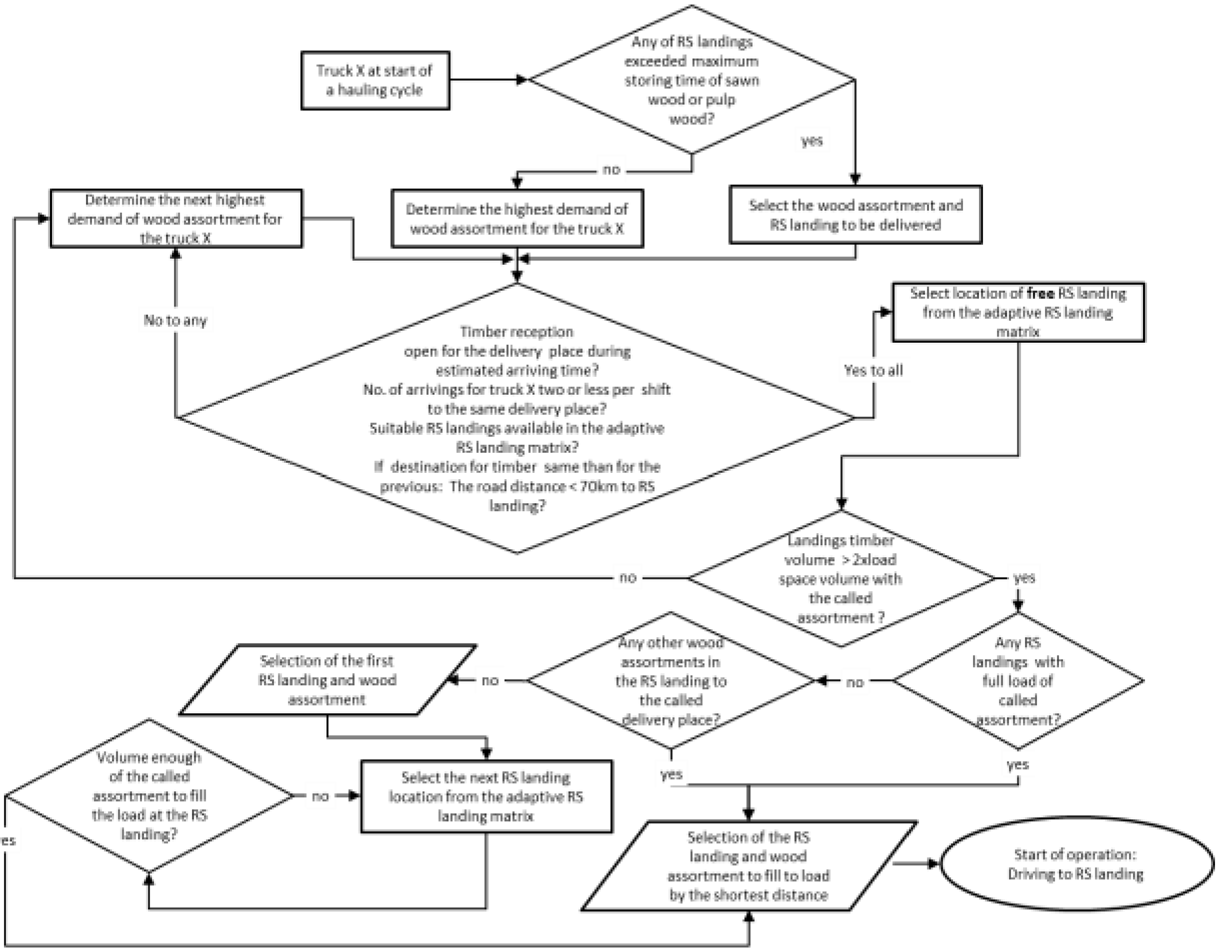

Figure 4. The logic for selecting the next RS landing, wood assortment and delivery place for the truck.

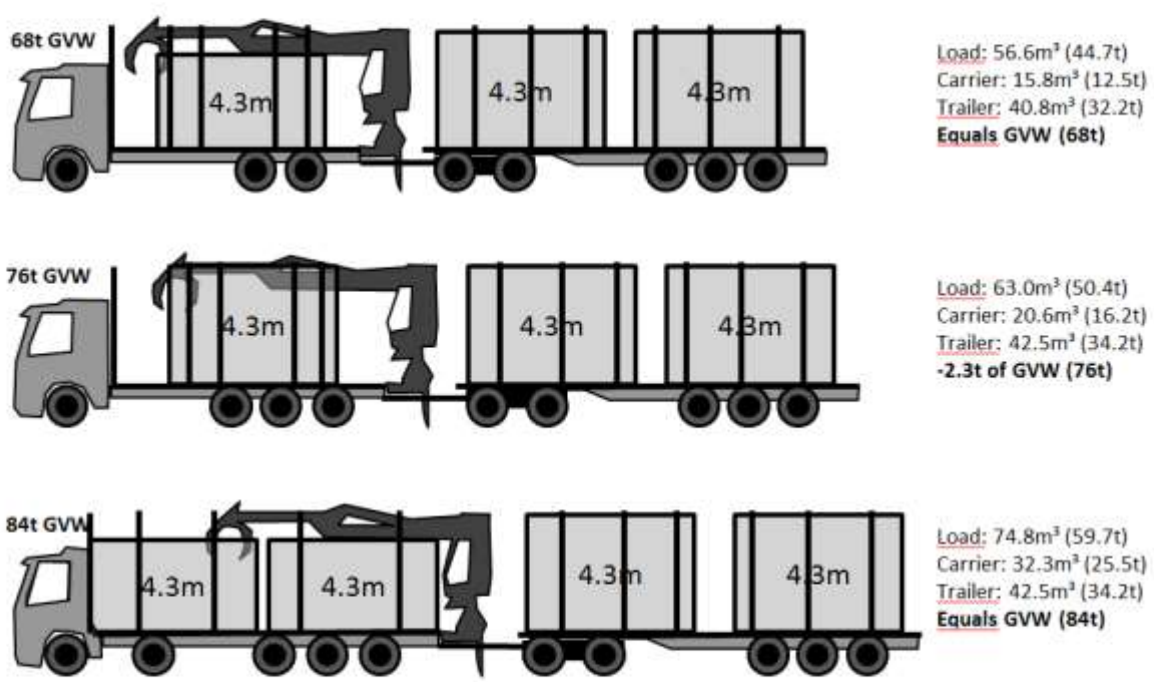

Figure 5. Studied timber trucks (GVWs of 68t, 76t and 84t) as loaded by fixed length of 4.3m spruce saw logs with the fresh weight density of 790kg/m³. Picture illustrates one example of fully loaded trucks either by the GVW or by available frame volume of the load space for the case timber assortment.

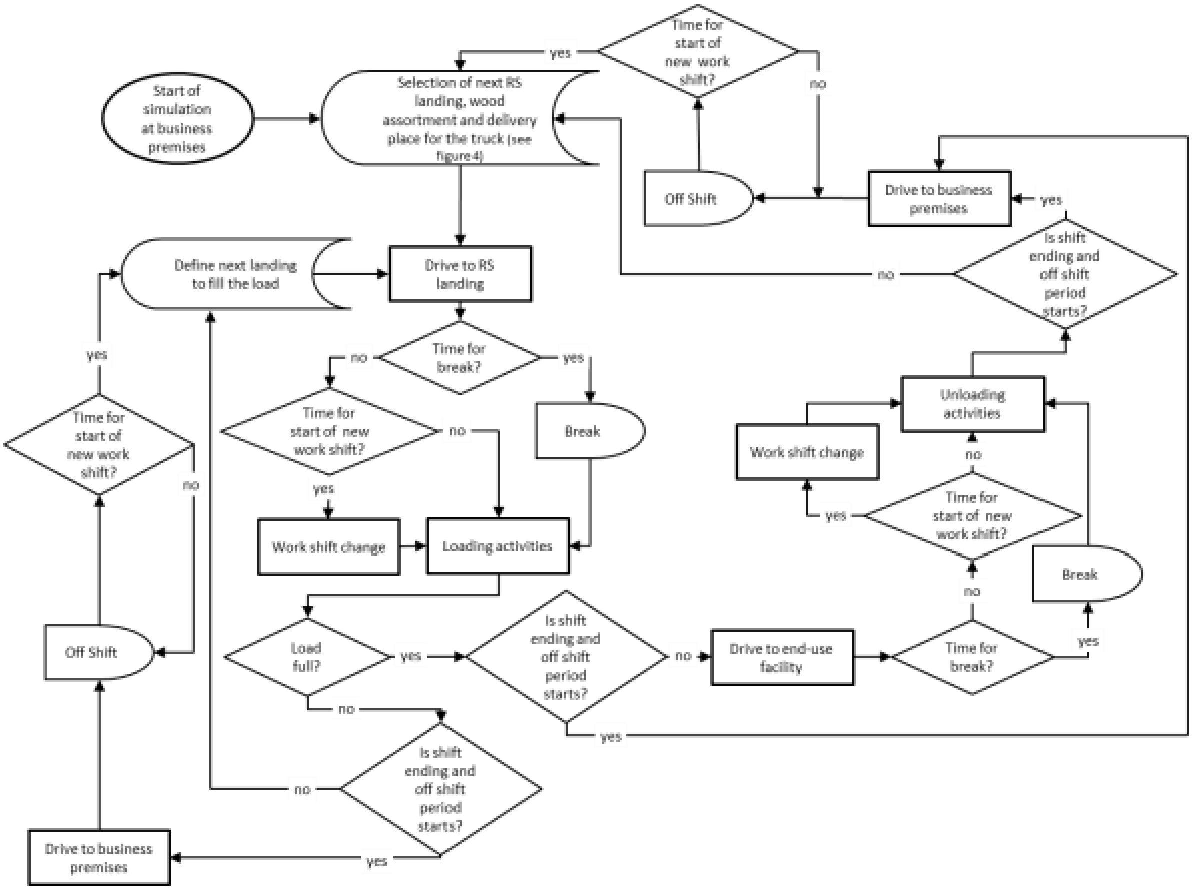

Figure 6. The logic of timber trucking in the simulation model.

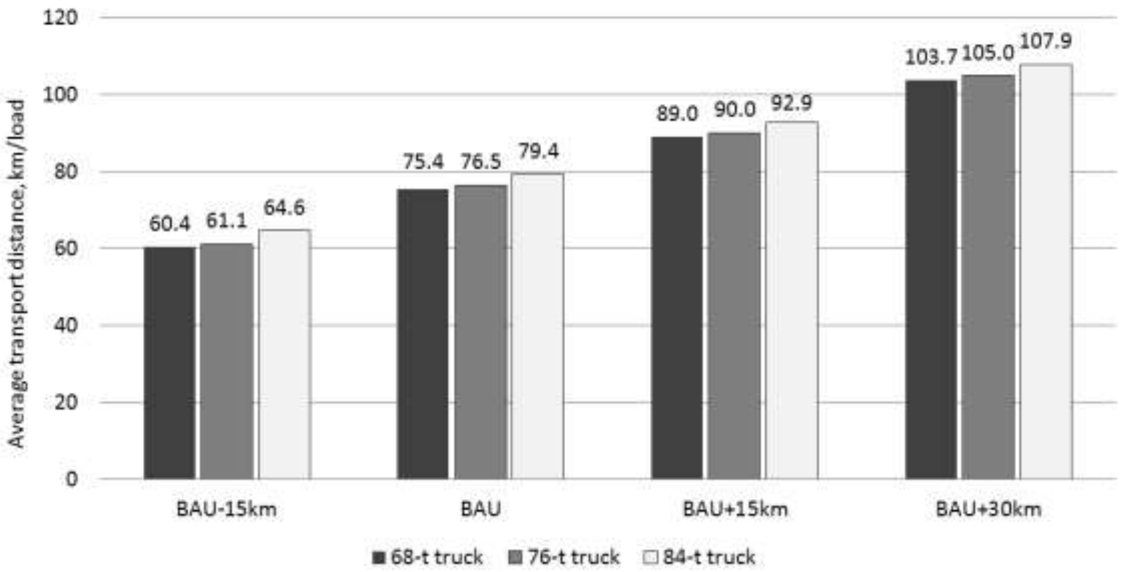

Figure 7. The average transport distance from the RS landing to the delivery place for each vehicle type in each distance scenario (the distance included loading, driving between RS landings, and driving loaded).

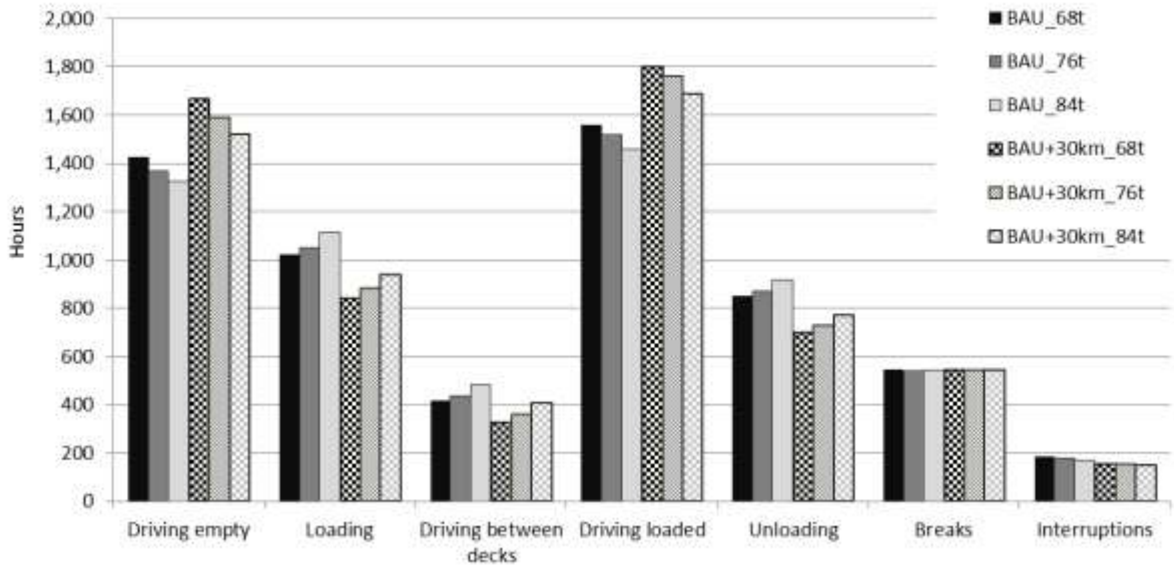

Figure 8. The work element distribution for each vehicle type in the BAU and BAU+30km scenarios for annual timber trucking. Loading and unloading times include waiting and interruptions associated with them.

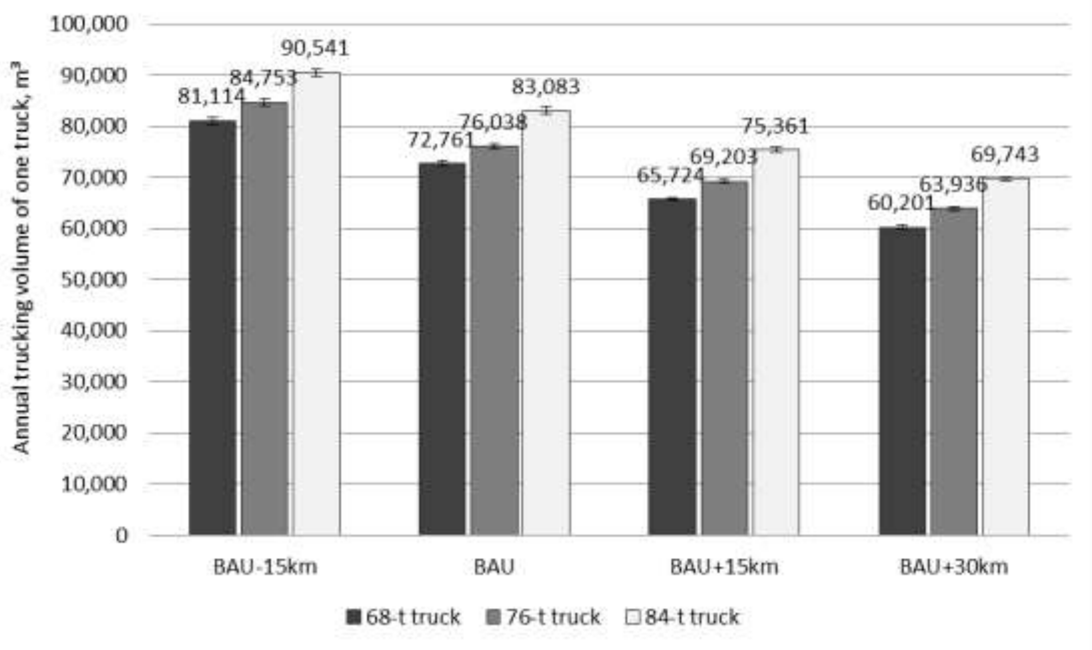

Figure 9. Annual timber trucking volume for the 68-, 76- and 84-tonners in four different distance scenarios with 15km distance intervals. 95% confidence intervals are expressed by the error bars.

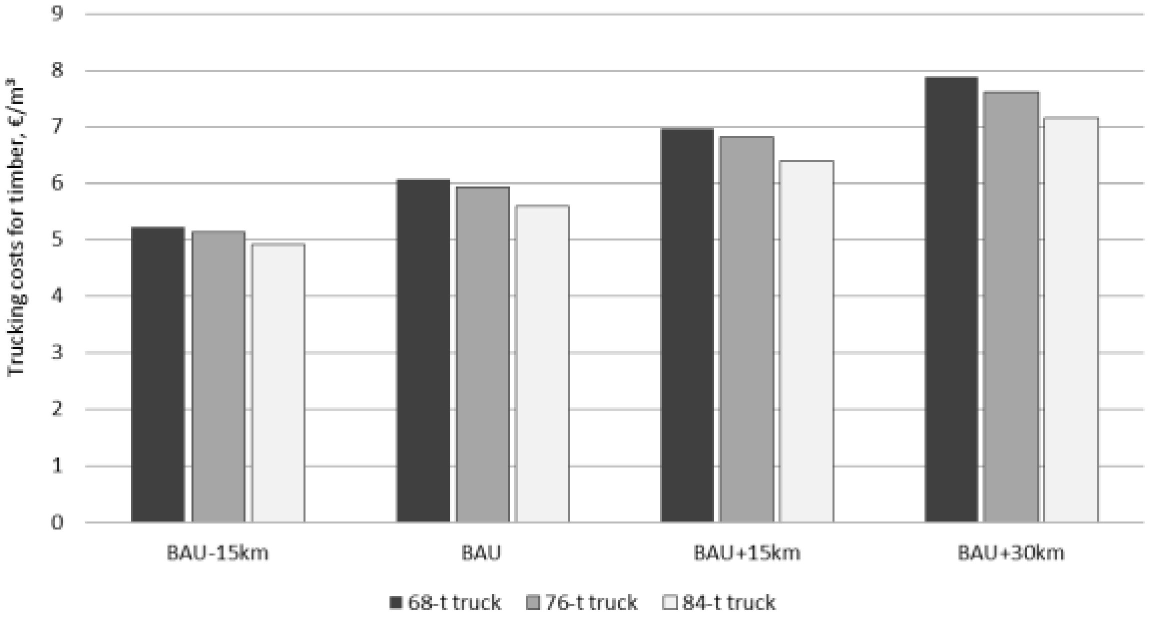

Figure 10. Timber trucking costs for the vehicle types in four distance scenarios.