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Could a terminal-based operating model reduce greenhouse-gas emissions in road transport of timber?

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ABSTRACT

Given the trucking companies' need to reduce fuel consumption and greenhouse gas (GHG) emissions during timber transport, efficient operating models are crucial. While multimodal transport is preferred for long distances, road transport remains the primary method in regions lacking rail or waterway connections. This study evaluated whether a terminal-based operation model could reduce GHG emissions in road transport of timber. A discrete-event simulation model was used to compare traditional direct timber deliveries with a terminal-based system in northern Finland. The results showed that the integration of a terminal increased transport efficiency, allowing a 10% higher timber volume to be delivered. At the same time, the fuel consumption and GHG emissions of the supply system were reduced by 4% per cubic meter of timber transported. The benefits stem from more efficient trucking with shorter trips and more frequent full truck loads from a single storage location with mixed-assortment loads. Although terminal-based logistics requires investment and introduces additional handling costs, the study suggests that it can enhance sustainability and operational efficiency. The findings highlight the potential for emission savings, but further research is needed to assess the economic feasibility of the terminal-based operating model and the impact of alternative trucks in outbound logistics. The simulation model can be adapted to other environments to evaluate broader applicability.

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Discrete-event simulation; log truck; pulpwood supply; timber terminal

Introduction

The European Union (EU) has established ambitious targets for the reduction of the greenhouse gas (GHG) emissions, including those from the transport sector. The European Green Deal aims to achieve a 90% reduction in transport emissions by 2050 compared to the emissions in 1990 levels (COM (2019) 640 final). Within the EU, Finland has set an even more ambitious target: domestic transport emissions should be reduced by 50% by 2030 and by 100% by 2045 compared to the emissions in 2005 (LVM 2021).

While the Green Deal emphasizes the shift from road to rail and waterway transport, multimodal transport is not possible in locations lacking a rail or waterway connection. Timber trucks play a dominant role in timber transport in Finland as well as globally (Kärhä et al. 2024). Despite the recent growth in rail and waterway transport, 68% of domestic roundwood was still transported by road to mill in 2023 (Strandström 2024). The most common vehicle configuration consists of a self-loading straight truck and a full trailer (later referred to as a truck) with a 76-tonne (t) gross vehicle weight (Venäläinen and Poikela 2024).

Logistic hubs (i.e., terminals) play a pivotal role in multimodal timber logistics, yet they offer numerous advantages in unimodal truck transport as well. Presently, they are commonly used to balance supply and demand fluctuations (Ylioja et al. 2021; Väätäinen et al. 2021; Davidsson et al. 2024; Kogler et al. 2025). An intermediate hub also enables the transport of full mixed-assortment loads from roadside storages to a terminal and full single-assortment loads further to mills. Otherwise, collecting a load with a single assortment may require visiting multiple roadside storages, thereby compromising transport efficiency (Venäläinen and Ovaskainen 2016).

The dearth of truck drivers has been a persistent issue in timber logistics (Malinen et al. 2014; Derochers et al. 2025; Kogler et al. 2025). Forest roads are a challenging working environment requiring skilled workforce. In contrast, the route between a terminal and a mill is likely paved and wide posing fewer skill requirements of drivers. Consequently, the recruitment of drivers for shuttle trucks operating between terminals and mills might be easier. In terminal-based delivery, transporting timber from forests to terminals shortens the trips of forest trucks thus improving the performance of forest trucks and their drivers. This reduces the need for forest truck drivers and creates a demand for drivers to operate shuttle trucks.

With respect to emissions, a shuttle truck may utilize alternative, low-emission or emission-free power sources, including biogas (Huuskonen 2024) and electricity (Uhrdin et al. 2023). In 2023, Finland produced 94% of its electricity from non-fossil sources (Statistics Finland 2024b). A High Capacity Transport (HCT) vehicle has been shown to emit lower levels of GHGs per tonne transported due to its increased payload capacity (Kärhä et al. 2023). In addition, there is no need for a crane in the shuttle truck, if there is a separate loader both at the

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terminal and the mill, which increases payload capacity. Furthermore, the separate loader can be electrified.

The disadvantage of a terminal-based logistical system is the extra costs on establishment and increased handling of timber. Although the transport distance of any individual truck load is longer via a terminal than if transported directly to a mill, in a complex transport system it is not self-evident that the total transport costs or emissions would increase. This needs to be clarified by research.

A range of operations research methodologies have been employed to examine truck-based timber and wood biomass supply from roadsides to facilities. Optimization methods have been used in operational planning to minimize transport costs and for routing of trucks (Rönnqvist 2003). Simulation techniques, on the other hand, are particularly well-suited for analyzing complex systems characterized by interactions and uncertainties (Banks et al. 2009).

Simulation modeling has been utilized to compare existing systems with new configurations based on performance indicators. For example, Windisch et al. (2015) used discrete-event simulation (DES) to compare the existing process for feedstock allocation with information-based decision making to better cope with demand peaks of a combined heat and power (CHP) plant. Later, Väätäinen et al. (2017) evaluated both the direct supply and a hybrid supply with direct and terminal-linked supply of forest chips to a CHP plant. Belbo and Talbot (2014) compared ten different supply chains of whole tree chips in terms of supply costs. In the context of timber transport Väätäinen et al. (2020) utilized DES to evaluate supply setups, such as truck sizes, with a view to enhancing system performance in terms of productivity, energy efficiency and costs. Another simulation technique, agent-based simulation, has been used, e.g. to seek an effective utilization of transshipment terminals and HCT trucks in the supply of pulpwood (Korpinen et al. 2019) and to compare supply chain options in mountainous regions (Kogler et al. 2020; Holzfeind et al. 2021).

The aim of this study was to assess whether a terminal-based operating model could reduce GHG emissions in road transport of timber compared to direct supply with timber trucks. DES was chosen as the study method because it enables accurate enough modeling of complex timber trucking logistics with system interactions and randomness.

Materials and methods

Operating environment

The case study was developed around a planned terminal location in the city of Oulu in Northern Finland (Figure 1). The transport company planning the terminal operates within an extensive supply region east of Oulu. With the increasing deliveries of pulpwood to Metsä Fiber's Kemi mill (started in 2023), the lengthening transport distances called for an alternative, emission-efficient solution. The supply region of the transport company has no rail or waterway connection, leaving truck transport the only viable option. The terminal would be used primarily for transporting pulpwood, as lead times for sawlogs are shorter. The transport company had nine trucks,

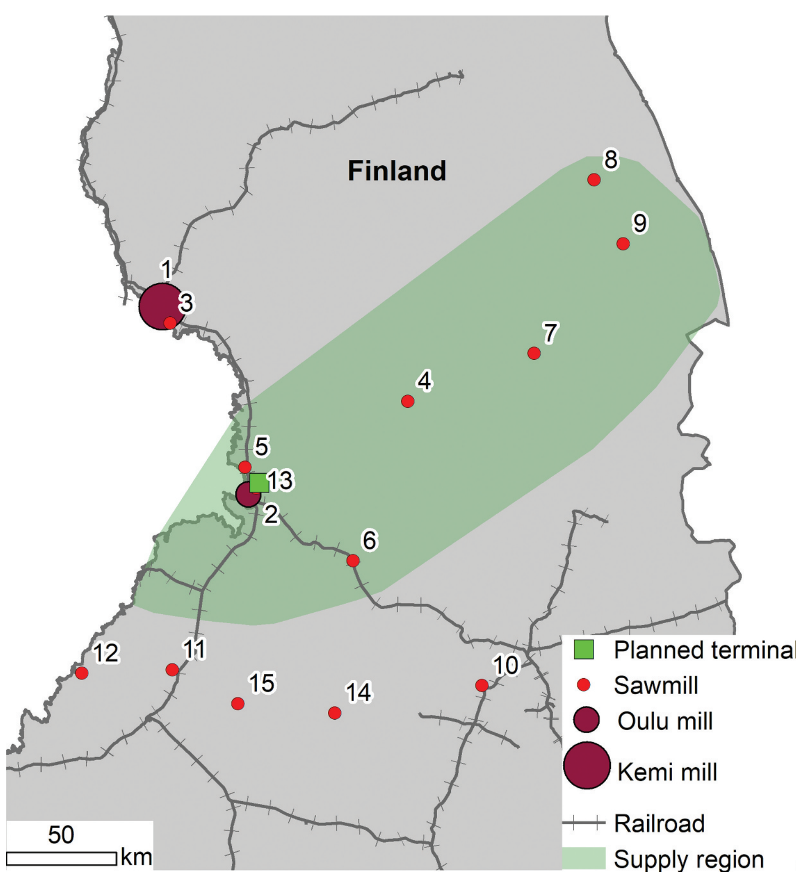

Figure 1. The operating area of the case study. The mill ids refer to Table 1.

and the goal was to compare operating models while keeping the number of trucks constant.

The transport company supplies pulpwood to the Kemi mill and the Stora Enso mill in Oulu. In addition, it delivers sawlogs to a total of 13 sawmills. Table 1 details the share of deliveries based on the company's estimate of the distribution of deliveries. In this study, the actual delivered volumes depend on the operating model.

For the sake of simplicity, the following three timber assortments were considered in the simulation: coniferous sawlogs, coniferous pulpwood, and birch pulpwood. The coniferous species included Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), while the birch species were downy birch (*Betula pubescens* Ehrh.) and silver birch (*Betula pendula* Roth).

The dataset on roadside storages, which was obtained from a timber procurement company, encompassed a total of 4,043 storages. The timber volume stored at these sites amounted to 1.012 million cubic meters, with 50% of the volume comprising pine pulpwood, 22% pine sawlogs, 19% birch pulpwood, 6% spruce sawlogs, and 3% spruce pulpwood. The average size of a roadside storage was 250 m^3, with a range from 1 to 5,500 m^3. The transport distance and time from each storage to the terminal and to each mill were calculated in GIS using the DigiRoad national road and street database (ESRI Finland 2022). An artificial forwarding date was randomly generated for every storage so that they were evenly distributed over the simulation period.

Simulation model

The DES model was implemented in Witness 27 by Royal HaskoningDHV. Within the model, trucks are represented by objects called "Parts," which move via "Paths" between storage and delivery locations, which are modeled as objects called "Machines."

A truck can be classified as either a forest truck (hereafter referred to as FT) operating from roadside storages to the mills and the terminal or a shuttle truck (ST) driving between the terminal and the two pulpmills. The operation logic of the FTs is detailed below. Furthermore, the FTs are used in two 12-hour shifts every weekday and on one 12-hour shift on Saturday. The first shift on Monday commences at 5:00 a.m., while the final shift on Saturday concludes at 5:00 p.m. In contrast, an ST is used every day in two 12-hour shifts.

The model's initialization involves the importation of several scenario-related key parameters, the monthly demand matrix by the mills, shifts, and a subset of storage data from an Excel file. The storage data is then read into a so-called active matrix, which represents a list of storages to which the transport company has access on a given day. Every morning the empty storages are removed, and new ones are imported to the active matrix. Following the simulation, key results are exported to another Excel file for further processing. The transport operations over a one-year time period were simulated with a one-minute time step. Prior to the recording of the results, a two-week warm-up period was run to ensure that the system had reached a steady state.

Operation logic of a forest truck

The simulation begins at the terminal by first selecting a destination, an assortment that is to be delivered, and a roadside storage for each FT (Figure 2). The selection procedure is explained below in detail. If a feasible destination and storage are found, an FT is directed to the storage. The final shift of the workweek will end at an earlier hour if such storage-destination pair cannot be found that could be delivered during the remaining shift time. Accordingly, the FT goes to off-shift mode until a new shift starts on Monday.

Upon arriving at a storage, the FT is loaded. A minor, 5 m^3 overload is accepted if it results in the emptying of the storage. If the FT gets a full load, it drives to the designated destination. Otherwise, it searches for a fill-up storage along the road to the delivery location. The maximum increase in travel time for multiple pickups is given as a parameter to the model. If

Table 1. Share of deliveries by destination and assortment.

Id	Location	Share of deliveries	Assortment
1	Kemi	20%	Birch pulpwood
1	Kemi	43%	Coniferous pulpwood
2	Oulu	11%	Coniferous pulpwood
3	Kemi	2%	Coniferous sawlogs
4	Pudasjärvi	2%	Coniferous sawlogs
5	Oulu	2%	Coniferous sawlogs
6	Utajärvi	2%	Coniferous sawlogs
7	Taivalkoski	2%	Coniferous sawlogs
8	Kitka	2%	Coniferous sawlogs
9	Kuusamo	2%	Coniferous sawlogs
10	Kajaani	2%	Coniferous sawlogs
11	Oulainen	2%	Coniferous sawlogs
12	Kalajoki	2%	Coniferous sawlogs
13	Oulu	2%	Coniferous sawlogs
14	Pyhäntä	2%	Coniferous sawlogs
15	Haapavesi	2%	Coniferous sawlogs

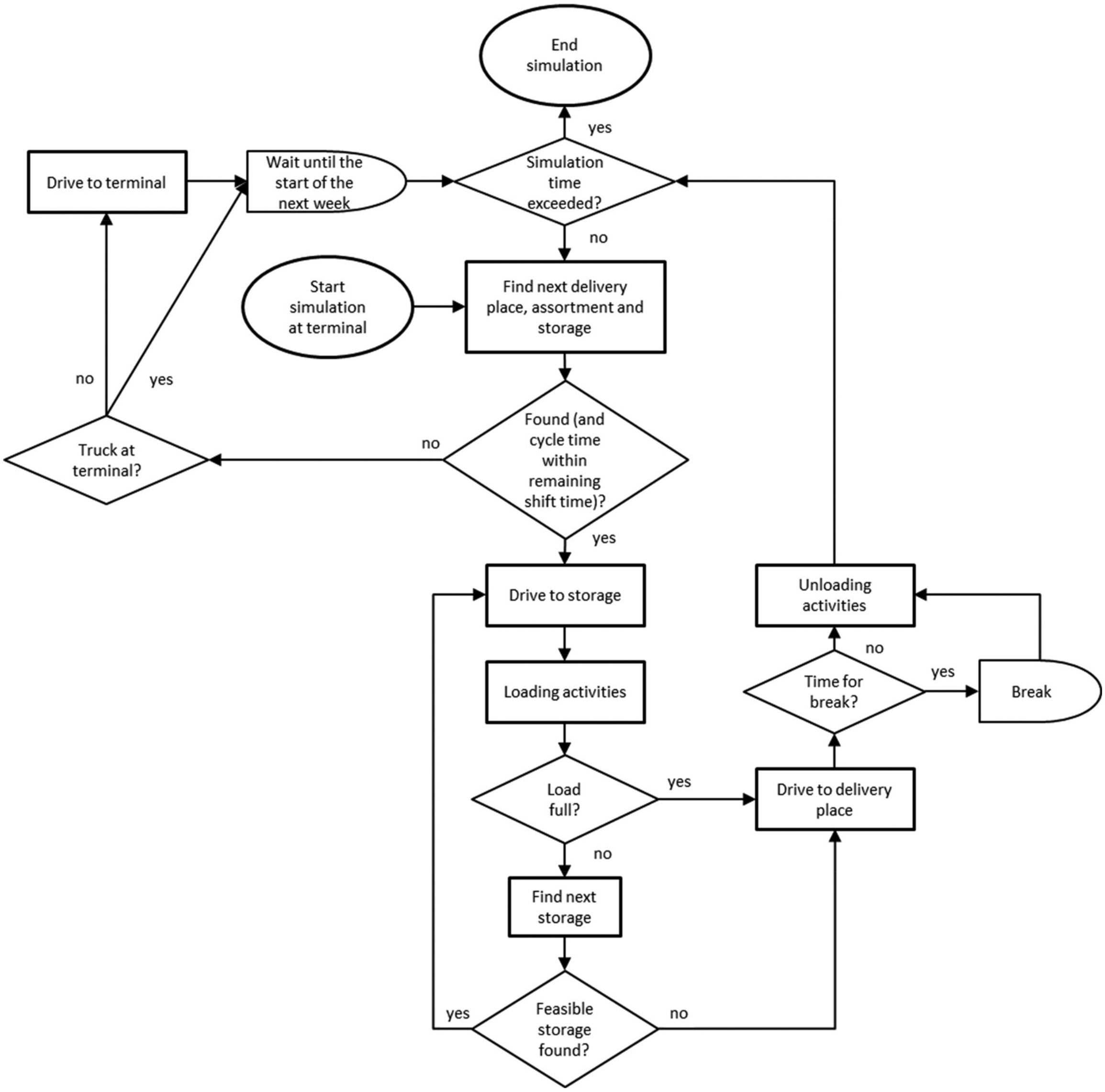

Figure 2. The action logic of a forest truck in the simulation model.

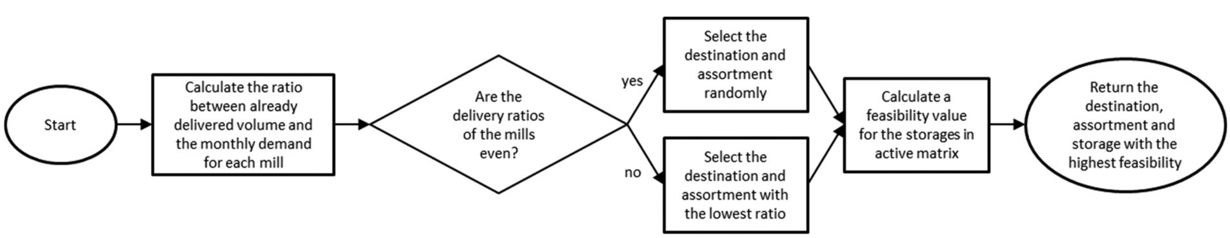

Figure 3. Selection procedure of the next destination, assortment, and storage. In the case study, the maximum difference between the ratios of monthly demand already delivered, maxDiffRatio, was set at 20%-units.

a feasible fill-up storage is found, the FT drives to the storage. Conversely, if such storage is not found, the trip continues directly to the destination.

At the destination, the FT driver takes a break, if necessary (Regulation (EC) No 561/2006). After this, the FT is unloaded. Finally, if simulation time is not yet exceeded, a new destination, assortment, and storage for the FT are selected.

The subsequent destination, assortment, and storage are selected in accordance with Figure 3. First, the ratio between the volume that has been delivered and the monthly demand is calculated for each mill. If the deliveries have been even, i.e. the difference between the ratios is less than the maximum allowed difference, a destination and assortment are selected randomly. In case the difference is higher, the (first) destination and assortment with the lowest relative ratio are selected. The following example clarifies the selection of the next mill: On the 12th September the sawmills have already received 48–65% of the demand of the month. However, the Kemi pulpmill has only received 45% and Oulu pulpmill 43% of the demand. As the difference between the highest and lowest ratio, 22 %-units, is higher than the maximum difference allowed (20 %-units), theOulu mill will be the next destination. After the selection, a storage is reserved for the truck.

Storage selection is based on storage feasibility value, which is evaluated for all storages in the active matrix. The storage with the highest feasibility value is then chosen. See Table A1 for an example of storage selection.

The value is set to zero for a storage under the following conditions:

(1) The storage is reserved by another truck OR
(2) The volume of the desired assortment is less than a preset minimum volume OR
(3) The trip time exceeds the remaining shift time.

Otherwise, the feasibility value for a storage is calculated as a function of travel and storage time, and storage volume (Eq. 1). First, the feasibility value increases with decreasing travel time, favoring nearby storages (Eq. 2). Second, the value increases strongly when the storage time approaches the maximum storage time (Eq. 3). This prevents timber from drying or rotting in a storage. Finally, storages that are smaller than a truck load are prioritized to clear out the landing site (Eq. 4). The explanatory variables and shapes of the models were determined heuristically through a visual examination of the simulation model run and feasibility values generated with varying input values.

$$storageFeasibility = travelTimeFeasibility + storageTimeFeasiblity + storageVolFeasibility \quad (1)$$

where

$$travelTimeFeasibility = -(drivingTimeOriginStorage + drivingTimeStorageDestination/backhaulFactor) + 1000 \quad (2)$$

drivingTimeOriginStorage = driving time in minutes from the origin (terminal/mill) to the storage,
drivingTimeStorageDestination = driving time in minutes from the storage to the destination (terminal/mill),
backhaulFactor = a weight given to driving with load,

$$storageTimeFeasiblity = (storageDays/maxStorageDays\_a)^3 * 1000 \quad (3)$$

storageDays = number of days since the storage was created, *maxStorageDays_a* = maximum number of storage days for assortment *a*,

$$storageVolFeasibility = \begin{cases} 1000, if storage volume < truck load size \\ 0, otherwise \end{cases} \quad (4)$$

In conjunction with the calculation of the feasibility value, the decision is made regarding whether the load will be transported directly or via the terminal. Transportation via the terminal is selected in instances where the following criteria are met:

(1) Terminals are allowed in the current scenario. AND
(2) Timber is not transported in the "wrong direction." For each roadside storage, a binary value indicating this was calculated before the simulation. At the terminal location, a line perpendicular to a line connecting the terminal and the mill was drawn, and the storages on the mill side of the line were deemed unsuitable for transport via the terminal. AND
(3) When the destination is Oulu mill, assortment volume is less than a truck load. This condition leaves full single-assortment loads to be delivered directly to a mill. When the destination is Kemi mill, also full single-assortment loads can be delivered to the terminal to maximize the capacity utilization of the ST. AND
(4) The monthly transport capacity of the ST is not exceeded. This criterion ensures that all timber stored at the terminal will be delivered to a mill before it deteriorates. AND
(5) The roadside storage is not too old (Eq. 5). Storages older than *minStorageDays2Terminal* are transported directly to a mill.

$$storageDays \le maxStorageDays\_a - minStorageDays2Terminal \quad (5)$$

where *minStorageDays2Terminal* = the minimum time before the storage is too old to be transported via terminal.

The operation logic is illustrated by an example on one week's trips of each truck type in Tables A2– A4.

Scenarios and parametrization

As the aim was to compare a terminal-based operating model to direct supply with timber trucks two scenarios were defined. In the business-as-usual (BAU) scenario, all nine FTs of the trucking company deliver pulpwood and sawlogs directly from roadside storages to the mills. In the Terminal scenario, however, one of the trucks was used as an ST to transport pulpwood from the terminal to the two mills located in Kemi and Oulu. A diesel-fueled separate loader, such as a log stacker, was assumed for both loading of the ST at the terminal and unloading of the ST at a mill. This allowed the ST to operate without a crane, which increased the load space by 5 m^3.

The number of full working weeks of the FTs was set at 38 to match the annual driving kilometers with the actual driving kilometers of the trucking company. The parameter values that control, e.g., a simulation run, truck load size, loading and unloading times, and maximum storage time of timber are given in Table 2. The loading and unloading times of both an FT and an ST were sampled from triangular distributions, where the minimum time was assumed to be 50% lower and the maximum time 50% higher than the mode. The time variation was set high because these work elements also

Table 2. General parameter values in the simulation model. FT = forest truck, ST = shuttle truck. Source: 1 = own choice/estimation, 2 = trucking entrepreneur, 3 = timber procurement company, 4 = Nurminen and Heinonen (2007).

Parameter	Explanation	Unit	Value	Source
avgLoadSelfloader	Mode of loading time for a fully laden FT with a self-loader	min	54	4
avgLoadSeparLoader	Mode of loading time for a fully laden ST with a separate loader	min	15	2
avgUnloadSelfloader	Mode of unloading time for a fully laden FT with a self-loader	min	30	2
avgUnloadSeparLoader	Mode of unloading time for a fully laden ST with a separate loader	min	15	2
backhaulFactor	Weight given to driving with load		10	1
loadSizeFT	Load size (normal maximum for FT)	m^3	60	2
loadSizeST	Load size (maximum for ST)	m^3	65	2
maxDiffRatio	Maximum accepted difference in ratios of monthly deliveries	%-units	20	1
maxIncreaseTravelTime	Maximum increase of driving time when finding another storage to fill the load	%	50	1
maxLoadSizeFT	Load size (temporary overload of FT to clear out a storage)	m^3	65	1
maxStorageDays_SLS	Maximum storage time of sawlogs in summer (Jun-Sep)	days	14	3
maxStorageDays_SLW	Maximum storage time of sawlogs in winter (Oct-May)	days	60	3
maxStorageDays_PW	Maximum storage time of pulpwood	days	60	3
maxTravelTimeStoMill	Maximum driving time from the storage to the mill in direct deliveries	min	600	1
minAssortmentVol	Minimum volume of the desired assortment in storage selection	m^3	5	1
minLoadSizeFT	Load size (minimum for a fully laden FT)	m^3	55	1
minStorageDays2Terminal	Minimum time before the storage is too old to be transported via terminal	days	2	1
nRowsPerFT	Number of rows in active storage matrix per truck		15	2
totalSimulationTime	Total simulation time including warmup	min	547,200	1
warmup	Warmup time after which the results will be recorded	min	21,600	1

Table 3. Scenario-specific parameter values in the simulation model.

Parameter	Explanation	BAU	Terminal
qtyFT	Number of forest trucks	9	8
qtyST	Number of shuttle trucks	0	1
loadSizeST	Maximum load size of a shuttle truck (m^3)	NA	65

included time elements, such as preparing of a truck and loader for the loading function and waiting/queuing for the unloading function at the terminal or mill. If less than the maximum volume was loaded or unloaded, the time distributions for an FT were calibrated with the ratio of the loaded volume to the maximum load size of the truck. Table 3 details the scenario-specific parameter values.

Fuel consumption and emissions

Based on the kilometers driven, fuel consumption and emissions were calculated in Excel after the simulations. For an FT, fuel consumption when driving laden was predicted as a function of transport distance, the size of payload and the transport season (Kärhä et al. 2023). The volumetric load was converted to tonnes by applying the average density of pine and spruce sawlogs and pine, spruce, and birch pulpwood over a year 0.843 tm^{-3} (Luke 2023). For fuel consumption when driving empty and driving between storages 45 $l(100\,km)^{-1}$ and 76 $l(100\,km)^{-1}$ was assumed, respectively (Anttila et al. 2023).

Because an ST mostly drives on highways and has lower tare mass than an FT, its fuel consumption when driving is lower than the one of the FT. Additionally, an ST may also have lower rolling resistance due to smoother tires and paved roads. Consequently, the fuel consumption of the ST was reduced by 3 $l(100\,km)^{-1}$ (driving laden) and by 5 $l(100\,km)^{-1}$ (driving empty) from Terminal to Kemi (107 km) compared to the consumption of a FT (cf. Venäläinen and Poikela 2024). However, on the 11-kilometer route from Terminal to Oulu, the consumption of the ST was assumed at the level of an FT. This assumption was made due to the short route comprising several junctions with accelerations and decelerations.

The fuel consumption of loading and unloading was based on the report by Poikela and Strandström (2023). The average values of loading and unloading with a self-loader were used for an FT (Table 4). For an ST, the fuel consumption of a separate loader was assumed. Fuel consumption when idling was not considered.

The calculation of GHG emissions followed the tank-to-wheel approach, meaning that only direct emissions were considered. The emission factor for converting fuel consumption to CO_2 emissions was computed as the product of the CO_2 emission factor of the fossil component, net calorific value, and density (Statistics Finland 2024a). The biogenic share of energy content in the fuel was assumed at 16% (Statistics Finland 2024a). To account for the non-CO_2 greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), the emission factor was augmented by 1.3% (Department for Energy Security and Net Zero 2023). Consequently, the final emission factor employed was 2.1508 kg $CO_2e\ l^{-1}$.

Results

The average trip distance for an FT was 303 km (154 km with load) and 223 km (115 km with load) in the BAU and Terminal scenarios, respectively (Table 5). The corresponding numbers for trip duration were 432 min and 340 min. Therefore, on average, the incorporation of a terminal within the system led to a 26% reduction in trip distance and a 21% reduction in trip

Table 4. Fuel consumption of load handling operations (lm^{-3}).

Work phase	Forest truck	Shuttle truck
Loading	0.1355	0.087
Unloading	0.0895	0.072

Table 5. Annual operational data for a forest truck (FT) and a shuttle truck (ST) in scenarios BAU and Terminal. After an estimate, the 95% confidence interval is presented.

Characteristic	FT (BAU)		FT (Terminal)		ST (Terminal)	
Number of trips[a]	672	[665, 678]	856	[843, 869]	2223	[2206, 2240]
Avg trip duration (min)[a]	432	[428, 436]	340	[334, 345]	232	[230, 233]
Avg trip distance (km)[a]	303	[300, 306]	223	[218, 228]	188	[187, 190]
driving empty	135	[133, 136]	105	[103, 108]	94	[93, 95]
driving laden	139	[138, 140]	105	[102, 108]	94	[93, 95]
driving between storages	15	[14, 16]	10	[10, 11]	N/A	N/A
Capacity utilization	55.2%	[55.1%, 55.3%]	55.3%	[55.1%, 55.4%]	98.1%	[97.5%, 98.7%]
Load size (m^3)	56.5	[56.0, 57.0]	56.1	[55.6, 56.5]	65.0	N/A
Share of full loads	88.4%	[87.1%, 89.7%]	86.7%	[85.6%, 87.8%]	100.0%	N/A
Transported volume (m^3)	37965	[37399, 38531]	47974	[47163, 48784]	144487	[143368, 145606]
Total distance (km)	205063	[204489, 205636]	191382	[189861, 192904]	418554	[415431, 421676]
Consumption (l(100 km^{-1}))[b]	55.1	[55.0, 55.1]	55.7	[55.6, 55.8]	51.8	[51.8, 51.8]
Emissions (kg CO_2e)[c]	261231	[260613, 261848]	252569	[251413, 253725]	515583	[511877, 519289]

[a]For FTs, empty return trips to terminal at the end of a shift excluded.
[b]When driving.
[c]Includes driving and load handling.

Table 6. Distributions of the number of loading events and assortments per trip for scenarios BAU and Terminal.

Characteristic	#	BAU	Terminal
Loading events	1	63.1%	76.4%
	2	33.3%	22.4%
	3	3.1%	1.0%
	4	0.4%	0.2%
	5	0.1%	0.0%
Assortments	1	100.0%	83.9%
	2	0.0%	15.4%
	3	0.0%	0.6%

duration for an FT, consequently increasing the number of trips by 27% and the timber transported by 26% (Table 5). The capacity utilization of the FTs in both scenarios was approximately 55%, while the ST operated at nearly full capacity. There were no major differences in the results between the simulation runs.

The average load size of the FTs was almost equal in the scenarios (Table 5). However, due to the possibility to transport mixed-assortment loads in the Terminal scenario, a full load was obtained more frequently already from the first storage than in the BAU scenario (Table 6). Nonetheless, mixed loads comprised a mere 16% of the number of deliveries in the Terminal scenario.

Because the ST's load handling operations were more efficient than the FTs', the ST could allocate more time to driving activities (Figure 4). On average, the share of driving of the worktime was 69%, 65%, and 78% for an FT in the BAU scenario, an FT in the Terminal scenario, and the ST, respectively.

The more efficient utilization of the trucks resulted in a 10% increase in timber deliveries in the Terminal scenario compared to the BAU scenario (Table 7). The increased transport performance for the Terminal scenario was due to the shorter trips and more frequent full truck loads from a single roadside storage with the option of either single or mixed-assortment load. The total volume of timber delivered via the terminal amounted to 144,487 m^3 of pulpwood and 5,457 m^3 of sawlogs, constituting 40% of the total supply. Concurrently, the Terminal scenario exhibited

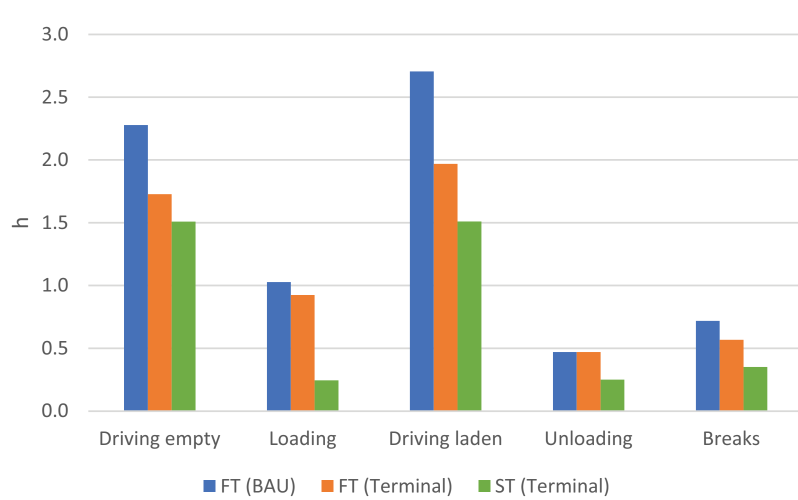

Figure 4. Trip-level work element distribution for each vehicle type in both scenarios. Queuing is included in the loading and unloading times.

Table 7. Key results by scenario over a one-year period.

Characteristic	BAU	Terminal
Number of trucks (FT/ST)	9/0	8/1
Performance (m^3)	343,260	378,111
Diesel consumption ($l(m)^{-3}$)	3.20	3.08
Emissions, driving (kg CO_2e m^{-3})	6.40	6.01
Emissions, load handling, FT (kg CO_2e m^{-3})	0.48	0.61
Emissions, total (kg CO_2e m^{-3})	6.88	6.63

a 4% reduction in fuel consumption and emissions when compared with the BAU scenario.

Discussion

In order to ensure the reliability of the results, it is imperative that the model is constructed in a meticulous manner and that the reference scenario, herein BAU, yields realistic outcomes. The BAU scenario closely resembled the actual situation when evaluated against the performance metrics of the forest truck transport cycle by the trucking company participating in this study. To verify the model, each logic function was tested individually, and the model was executed step by step. The correct movement of the trucks was also visually verified. Furthermore, certain parameter values were obtained from the trucking company (Table 2), the annual mileage was adjusted to align with the observed mileage, and real road network and timber storage data were utilized.

The simulation model comprised a detailed transport model, in which the movements of timber trucks were determined by demand for timber by mills, available roadside stocks, and operational rules and constraints. The primary logics embedded within the system were modeled to ensure a more reliable comparison of the scenarios. Special attention was given to the rules for selecting the next storage and between direct transport and transport via the terminal. The importance of the transport planning functionality in DES to closely mimic the actual wood supply chain was also noted by Westlund et al. (2024). Notably, the Terminal scenario incorporated two distinct rules that deviated from the current operating model (BAU): (i) the possibility to transport multi-assortment loads to the terminal, and (ii) the reduction of long forest truck trips by storing pulpwood at the terminal instead of transporting it directly to Kemi.

The load size was kept constant regardless of the type of timber transported or the season, as it did not have a significant effect on the comparison of the scenarios. As demonstrated in the study by Väätäinen et al. (2020), in practice the load size is influenced by the fresh density and the dimensions of logs. Additionally, tare weights of timber trucks have been found to increase during the winter months due to the accumulation of snow load and the deployment of winter equipment, which results in a reduction of the payload capacity (Anttila et al. 2020). Furthermore, an operating model where the self-loader is left at the roadside to be retrieved during the subsequent cycle may be feasible when transporting to a mill or terminal with its own unloading facilities. Removing the self-loader can increase the payload size by up to four tonnes (Anttila et al. 2022). Here, the self-loader was consistently attached to all forest trucks. In the study by Palander et al. (2020), based on load data from an enterprise resource planning system, the average load size was 50.5 t, which is higher than that observed in the BAU scenario (59.9 m^3 assuming the average density of 0.843 tm^{-3} vs. 56.5 m^3). The factors affecting the load size can be considered in future studies.

In this study, the size of the terminal was not predetermined, but the total transport capacity of a shuttle truck determined the throughput of the terminal. The terminal handled a total of 149,944 m^3 of the delivered timber volume. This is less than the throughput of railway terminals that utilize a separate loader (Venäläinen et al. 2021). Therefore, the terminal throughput should probably be higher in order to justify separate loading equipment for the ST, but this should be verified with a cost calculation.

A simplifying assumption was made that an FT would always use a self-loader for unloading, regardless of the destination. In practice, self-loaders are typically utilized for unloading at small sawmills and terminals. Separate loaders, on the other hand, are more commonly used at pulpmills, large sawmills and large terminals. Nevertheless, this assumption does not change the conclusions. Actually, assuming a separate loader for the FTs would have favored the terminal scenario, since unloading takes a larger share of the transport cycle than in the BAU scenario.

It was assumed that the supply and demand of timber remained constant. In practice, fluctuations in supply and demand are balanced through the utilization of temporary storage facilities, such as terminals. Including this would further increase the throughput of the terminal. The effect of varying supply and demand on the results should be assessed in a subsequent study.

The terminal scenario allowed the forest truck to achieve on average 26% higher annual transport volumes compared to the BAU scenario due to a significantly shorter trip distance and more frequent full truck loads from a single roadside storage with mixed-assortment loads. Terminal-based supply thus improves the transport performance of forest trucks, but also reduces the need for FTs and FT drivers and alleviates transport entrepreneurs' stress due to the shortage of skilled truck drivers.

The results reveal that in this operating environment, a terminal-based trucking concept would have lower emissions than the conventional direct delivery. Although the number of load handling operations per m^3 increases by 20% in the Terminal scenario, the total driving kilometers per m^3 decrease by 3%. In addition, the ST has lower emissions than an FT.

According to Poikela and Strandström (2023), the average emission intensity of direct truck transport of timber in Finland in 2022 was 4.3 kg CO_2e m^{-3}, while in this study the intensity was higher, 6.9 kg CO_2e m^{-3}. The difference can be explained by the longer transport distances in northern Finland and possibly also by lower load sizes in the simulation and different fuel consumption models. In this study, transport distances were found to be significantly longer (154 km in the BAU scenario) than the Finnish average of 105 km (Strandström 2024), mainly due to the more dispersed location of mills and the absence of railways.

An additional benefit of the terminal-based operating model is that it allows for even greater emission savings through the use of alternative energy sources for an ST and in material handling operations. This potential should be quantified in a further study.

It should be noted that the results of this study are only valid for this operating environment. Thereby, implementing a terminal-based operating model beyond the case study area may present a few challenges. Valipour et al. (2024) highlighted usual problems associated with establishing biomass terminals, some of which may also be relevant for roundwood terminals:

(1) High Initial Investment and Operating Costs. The terminal-based operating model requires investments in the terminal itself, as well as in a material handling machine and possibly also a low-emission ST. The terminal does not have to be paved; a large enough area with year-round access is sufficient. Should the ST and/or material handling be electrified, a charging possibility is needed. Therefore, a cost assessment and comparison to direct transport should be carried out.
(2) Location Selection. The terminal location should minimize overall cost, provide access to high-volume roads, and have acceptable environmental and social effects on the surrounding area. The benefits of a truck terminal are not obvious when transport distances are short or when there is a railway connection. However, the developed simulation model can be adapted to different environments.
(3) Land Availability. Other land uses, particularly residential and agricultural uses, may restrict land availability.
(4) Ownership. In the current study, the terminal was assumed to be solely owned and operated by one transport company. To enable higher throughput and lower fixed costs, however, a terminal could be shared by two or more companies. This would require clear contracts, adequate coordination, and data sharing between the companies.

Conclusions

A terminal-based operating model could potentially provide solutions to the various logistical challenges faced by timber trucking companies. In the operating environment of this case study, a moderate reduction in fuel consumption and GHG emissions, and the possibility of even greater emission savings with alternative shuttle trucks was discovered. At the same time, the volume transported could be increased with less forest truck drivers, which may help in driver recruitment. With the developed simulation model the suitability of the operating model can be evaluated in any other environment. Further research is needed to determine the additional emission-saving potential of low-emission shuttle trucks and trucking costs.

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APPENDIX A

Table A1. An example of ranking the storages in the active matrix based on feasibility values. In the example the truck is leaving the terminal on September 15 to transport pine pulpwood to Kemi. Based on the highest *storage Feasibility* storage 1532 would be selected. In the terminal scenario the load could be delivered to the terminal.

			Volume (m^3)						Driving time (min)							
Storage id	Forwarding date (YYYMMDD)	storageDays	Pine sawlogs	Pine pulpwood	Spruce sawlogs	Spruce pulpwood	Birch pulpwood	Reserved	Terminal	Kemi pulpmill	travelTime Feasibility	storageTime Feasibility	storageVolFeasibility	storageFeasibility	Correct direction	Note
1532	20170722	55	0	49	0	0	0	0	213	272	760	770	1000	2530	1	
713	20170816	30	0	48	0	0	0	0	185	450	770	125	1000	0	1	a
934	20170910	5	0	137	0	0	0	0	30	125	958	1	0	958	0	
3062	20170910	5	0	0	0	0	8	0	98	128	889	1	1000	0	0	b
2200	20170910	5	0	909	0	0	60	0	229	221	749	1	0	749	1	
516	20170910	5	0	4	57	34	544	0	77	170	906	1	0	0	0	b
273	20170911	4	0	141	0	0	0	0	52	145	934	0	0	934	0	
700	20170912	3	0	71	0	0	0	0	195	223	783	0	0	783	1	
2861	20170912	3	5	15	0	0	0	0	79	172	904	0	1000	1904	0	
1709	20170912	3	0	251	0	0	0	3	24	86	967	0	0	0	0	c
930	20170912	3	0	493	0	0	271	0	60	158	924	0	0	924	1	
920	20170912	3	0	84	0	0	0	0	67	160	917	0	0	917	1	

a. The trip time exceeds the remaining shift time.
b. The volume of the desired assortment is less than a preset minimum volume.
c. The storage is reserved by another truck.

Table A2. An example of one week's trips of a forest truck in scenario BAU. The origin and destination ids refer to the mill ids in table 1 and Figure 1 (T is for terminal).

Trip number	Origin id	Start time	Driving empty (km)	Driving laden (km)	Driving between storages (km)	Number of loadings	Total load volume (m^3)	Number of assortments	Destination id	End time	Day of the week
82	T	2017–09-18T05:00:00	201	285	63	2	60	1	1	2017–09-18T15:36:00	Mon
83	1	2017–09-18T17:20:00	131	162	45	2	60	1	1	2017–09-19T00:03:00	Tue
84	1	2017–09-19T01:33:00	165	165	0	1	60	1	1	2017–09-19T07:52:00	Tue
85	1	2017–09-19T09:05:00	140	163	68	3	60	1	1	2017–09-19T17:11:00	Tue
86	1	2017–09-19T18:35:00	140	140	0	1	60	1	1	2017–09-19T23:54:00	Tue
87	1	2017–09-20T00:56:00	181	181	0	1	60	1	1	2017–09-20T07:15:00	Wed
88	1	2017–09-20T08:33:00	162	162	0	1	60	1	1	2017–09-20T14:39:00	Wed
89	1	2017–09-20T15:50:00	162	152	12	2	60	1	1	2017–09-20T22:59:21	Wed
90	1	2017–09-21T00:15:21	152	152	0	1	60	1	1	2017–09-21T06:03:21	Thu
91	1	2017–09-21T07:20:21	134	134	0	1	55	1	1	2017–09-21T12:19:21	Thu
92	1	2017–09-21T13:29:21	152	168	60	2	60	1	1	2017–09-21T21:36:33	Thu
93	1	2017–09-21T23:03:33	138	138	0	1	60	1	1	2017–09-22T04:42:33	Fri
94	1	2017–09-22T05:52:33	144	163	64	3	60	1	1	2017–09-22T13:49:04	Fri
95	1	2017–09-22T15:14:04	144	144	0	1	60	1	1	2017–09-22T21:04:04	Fri
96	1	2017–09-22T22:11:04	176	159	24	2	60	1	1	2017–09-23T05:34:31	Sat
97	1	2017–09-23T06:46:31	129	45	0	1	57	1	2	2017–09-23T11:06:31	Sat
98	2	2017–09-23T12:07:31	35	35	0	1	37	1	13	2017–09-23T13:45:31	Sat
99	13	2017–09-23T14:16:31	22	22	0	1	6	1	13	2017–09-23T15:19:31	Sat
100	13	2017–09-23T15:43:31	4	0	0	0	0	0	T	2017–09-23T15:49:31	Sat

Table A3. An example of one week's trips of a forest truck in scenario Terminal. The origin and destination ids refer to the mill ids in table 1 and Figure 1 (T is for terminal).

Trip number	Origin id	Start time	Driving empty (km)	Driving laden (km)	Driving between storages (km)	Number of loadings	Total load volume (m^3)	Number of assortments	Destination id	End time	Day of the week
97	T	2017–09-18T05:00:00	80	80	1	2	60	1	13	2017–09-18T08:55:59	Mon
98	13	2017–09-18T09:42:59	63	60	10	2	60	1	2	2017–09-18T13:03:57	Mon
99	2	2017–09-18T14:02:57	56	55	0	1	55	1	13	2017–09-18T16:44:57	Mon
100	13	2017–09-18T17:42:57	243	31	0	1	60	1	9	2017–09-18T22:49:57	Mon
101	9	2017–09-18T23:55:57	226	128	0	1	60	1	11	2017–09-19T06:22:57	Tue
102	11	2017–09-19T07:37:57	69	156	0	1	60	1	3	2017–09-19T11:52:57	Tue
103	3	2017–09-19T12:48:57	156	208	0	1	57	1	7	2017–09-19T19:20:57	Tue
104	7	2017–09-19T20:32:57	92	144	0	1	60	2	T	2017–09-20T01:11:57	Wed
105	T	2017–09-20T02:09:57	215	133	0	1	60	1	4	2017–09-20T08:29:57	Wed
106	4	2017–09-20T09:47:57	134	72	0	1	60	1	8	2017–09-20T14:07:57	Wed
107	8	2017–09-20T15:07:57	199	67	0	1	60	2	T	2017–09-20T20:10:57	Wed
108	T	2017–09-20T21:19:57	68	166	0	1	60	1	14	2017–09-21T02:20:57	Thu
109	14	2017–09-21T03:24:57	89	133	0	1	60	1	10	2017–09-21T07:42:57	Thu
110	10	2017–09-21T08:58:57	161	39	36	2	60	1	T	2017–09-21T13:54:52	Thu
111	T	2017–09-21T15:09:52	87	87	0	1	60	1	T	2017–09-21T18:57:52	Thu
112	T	2017–09-21T20:06:52	87	95	0	1	60	1	2	2017–09-21T23:50:52	Thu
113	2	2017–09-22T00:45:52	35	39	0	1	59	2	T	2017–09-22T02:55:52	Fri
114	T	2017–09-22T03:43:52	39	39	0	1	37	1	T	2017–09-22T05:32:52	Fri
115	T	2017–09-22T06:03:52	0	11	0	0	60	1	5	2017–09-22T06:17:52	Fri
116	5	2017–09-22T06:57:52	86	40	61	2	60	2	T	2017–09-22T11:45:52	Fri
117	T	2017–09-22T12:37:52	55	55	0	1	60	1	T	2017–09-22T15:11:52	Fri
118	T	2017–09-22T16:07:52	79	92	0	1	60	1	12	2017–09-22T20:03:52	Fri
119	12	2017–09-22T21:03:52	48	91	0	1	60	1	T	2017–09-22T23:45:52	Fri
120	T	2017–09-23T00:38:52	55	51	0	1	60	1	2	2017–09-23T03:29:52	Sat
121	2	2017–09-23T04:21:52	30	26	9	2	56	2	T	2017–09-23T07:17:04	Sat
122	T	2017–09-23T08:08:04	41	41	0	1	60	1	T	2017–09-23T10:28:04	Sat
123	T	2017–09-23T11:14:04	29	29	0	1	37	1	T	2017–09-23T12:59:04	Sat
124	T	2017–09-23T13:40:04	29	29	0	1	27	1	T	2017–09-23T15:17:04	Sat

Table A4. An example of one week's trips of a shuttle truck in scenario Terminal. The origin and destination ids refer to the mill ids in table 1 and Figure 1 (T is for terminal).

Trip number	Origin id	Start time	Driving empty (km)	Driving laden (km)	Total load volume (m^3)	Destination id	End time	Day of the week
290	T	2017–09-18T00:54:09	107	107	65	1	2017–09-18T04:26:51	Mon
291	T	2017–09-18T05:09:51	11	11	65	2	2017–09-18T05:58:48	Mon
292	T	2017–09-18T06:18:48	107	107	65	1	2017–09-18T09:59:14	Mon
293	T	2017–09-18T10:42:14	11	11	65	2	2017–09-18T11:28:14	Mon
294	T	2017–09-18T11:45:14	107	107	65	1	2017–09-18T15:21:22	Mon
295	T	2017–09-18T15:54:22	107	107	65	1	2017–09-18T19:35:51	Mon
296	T	2017–09-18T20:11:51	11	11	65	2	2017–09-18T21:05:39	Mon
297	T	2017–09-18T21:27:39	107	107	65	1	2017–09-19T01:09:20	Tue
298	T	2017–09-19T01:50:20	11	11	65	2	2017–09-19T02:41:57	Tue
299	T	2017–09-19T03:04:57	107	107	65	1	2017–09-19T06:46:05	Tue
300	T	2017–09-19T07:30:05	107	107	65	1	2017–09-19T11:10:53	Tue
301	T	2017–09-19T11:48:53	107	107	65	1	2017–09-19T15:32:12	Tue
302	T	2017–09-19T16:10:12	107	107	65	1	2017–09-19T19:48:51	Tue
303	T	2017–09-19T20:29:51	107	107	65	1	2017–09-20T00:06:03	Wed
304	T	2017–09-20T00:42:03	107	107	65	1	2017–09-20T04:22:17	Wed
305	T	2017–09-20T04:52:17	107	107	65	1	2017–09-20T08:31:42	Wed
306	T	2017–09-20T09:08:42	107	107	65	1	2017–09-20T12:53:43	Wed
307	T	2017–09-20T13:32:43	107	107	65	1	2017–09-20T17:15:54	Wed
308	T	2017–09-20T17:58:54	107	107	65	1	2017–09-20T21:42:24	Wed
309	T	2017–09-20T22:18:24	107	107	65	1	2017–09-21T01:58:17	Thu
310	T	2017–09-21T02:31:17	107	107	65	1	2017–09-21T06:10:39	Thu
311	T	2017–09-21T06:48:39	107	107	65	1	2017–09-21T10:28:50	Thu
312	T	2017–09-21T11:06:50	107	107	65	1	2017–09-21T14:42:08	Thu
313	T	2017–09-21T15:24:08	107	107	65	1	2017–09-21T19:05:58	Thu
314	T	2017–09-21T19:46:58	107	107	65	1	2017–09-21T23:28:55	Thu
315	T	2017–09-22T00:01:55	107	107	65	1	2017–09-22T03:44:15	Fri
316	T	2017–09-22T04:24:15	107	107	65	1	2017–09-22T08:09:19	Fri
317	T	2017–09-22T08:44:19	107	107	65	1	2017–09-22T12:22:42	Fri
318	T	2017–09-22T13:05:42	107	107	65	1	2017–09-22T16:49:19	Fri
319	T	2017–09-22T17:31:19	107	107	65	1	2017–09-22T21:06:13	Fri
320	T	2017–09-22T21:43:13	107	107	65	1	2017–09-23T01:21:12	Sat

(*Continued*)

Table A4. (Continued).

Trip number	Origin id	Start time	Driving empty (km)	Driving laden (km)	Total load volume (m^3)	Destination id	End time	Day of the week
321	T	2017–09-23T02:03:12	107	107	65	1	2017–09-23T05:39:15	Sat
322	T	2017–09-23T06:18:15	107	107	65	1	2017–09-23T09:58:09	Sat
323	T	2017–09-23T10:38:09	107	107	65	1	2017–09-23T14:20:02	Sat
324	T	2017–09-23T14:56:02	107	107	65	1	2017–09-23T18:33:07	Sat
325	T	2017–09-23T19:08:07	107	107	65	1	2017–09-23T22:49:10	Sat
326	T	2017–09-23T23:27:10	107	107	65	1	2017–09-24T03:08:04	Sun
327	T	2017–09-24T03:45:04	107	107	65	1	2017–09-24T07:20:04	Sun
328	T	2017–09-24T07:59:04	107	107	65	1	2017–09-24T11:36:54	Sun
329	T	2017–09-24T12:15:54	107	107	65	1	2017–09-24T16:00:56	Sun
330	T	2017–09-24T16:40:56	107	107	65	1	2017–09-24T20:17:52	Sun
331	T	2017–09-24T20:54:52	107	107	65	1	2017–09-25T00:31:17	Mon