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Theoretical Potentials of Forwarder Trailers with and without Axle Load Restrictions

Ola Lindroos, Iwan Wästerlund

Abstract

In mechanized ground-based forestry, machines operate on rough soils that, ideally, should remain unaffected by the operation. This implies small (that is, light) loads and careful driving are required. However, economical rationality implies large loads and high speeds. Recently, the concept of adding a trailer to a conventional forwarder has been revived, with the objective of addressing both concerns, and fitting into the current, mechanized, cut-to-length system. Here we present the theoretical benefits of the forwarder-trailer concept compared to conventional forwarding for final-felling operations. The analysis addresses the trailer potential in terms of break-even extraction distances under different scenarios, and estimates the abundance of favorable conditions (as a percentage of final-felling volume) in Swedish final fellings. The results show that the forwarder-trailer concept has potential to reduce costs, and especially if there are restrictions on axle loads. However, the viability of the trailer concept is highly sensitive to changes in the increased purchase costs and the increased work-element time-consumption. That is, small changes in these variables result in large changes in viability. In the scenarios presented here, the increase in time consumption was more influential than the purchase cost. It can be concluded that there are potential economic and possibly also environmental benefits that warrant further investigation of the forwarder-trailer concept, which is currently being evaluated in practice in Sweden.

Keywords: forwarder, ground pressure, productivity, cost-efficiency, fuel consumption, theoretical potentials, comparative study

1. Introduction

In mechanized forestry, machines operate on rough soils that, ideally, should remain unaffected by the operation. However, large masses such as trees and logs are handled and, thus, the machines are often heavy. Machine masses are especially high in the work of transporting trees or logs from the terrain to roadside landing points, as it is generally time- and cost-effective to maximize payloads as well as transport speed. Thus, there is generally a conflict between minimizing soil disturbance and maximizing operational efficiency. A cause of soil damage is the year-round harvesting employed to supply industry with timber. The increased frequency of rainy periods and the reduction in frozen ground in northern Europe expected as a result of ongoing climate change will effect forest operations (Goltsev and Lopatin 2013) by increasing soil moisture content and reducing its bearing capacity and tensile strength. Good planning before harvesting should steer the operation towards better areas, but heavy rains can alter conditions very fast. Thus, even with good planning, the axle loads may become too heavy for the machinery used and there may be too little traction for the soil characteristics, which would create deep rutting and soil compaction (Wästerlund 1992, Nadezhdina et al. 2006, Sirén et al. 2013). Lately, there have been increased concerns about soil damage from harvesting operations, resulting in restrictions on where machines can travel and on their ground pressure (Horn et al. 2004, 2007). As ground pressure is the product of the force applied and the size of the supporting area, a decrease in ground pressure can be achieved by decreasing the force (i.e. axle loads) and increasing the supporting area, either separately or in conjunction. This implies that the total mass of the machines should be decreased, which can be achieved with a decreased payload for a given machine, or with a constant payload but with a lighter machine. The supporting area can also be increased, by increasing the wheel diameter and widths, using bogie tracks, or even by adding extra axles/wheels.

An alternative to the modification of currently used machines is to introduce new machine concepts. For instance, it has previously been suggested that forwarders could be equipped with a semi-trailer to increase the total payload transported and tests have indicated that the use of semi-trailers is cost-effective if transport distances are long (Eriksson 1998). However, the cost-effectiveness is very sensitive to the level of the increased cost implied by using the semi-trailer compared to only using a conventional forwarder. From here on, the term trailer will be used for all vehicles with increased load-space that can be attached to a forwarder, irrespective of type and of the fact whether they are powered or not (for example, including semi-trailers).

The use of a trailer can be reconsidered despite the fact that this has previously been found to be not economically viable compared to a conventional forwarder (Eriksson 1998). First, with potential restrictions on maximum ground pressure during forwarding, conventional forwarders might not be able to fully use their load capacity, which would increase the cost per transported unit for such a conventional system. Second, trailers admit larger payloads that can be distributed on additional axles and larger supporting areas than with conventional forwarders. Hence, trailers might admit larger loads with decreased ground pressure. Moreover, one of the previously found limitations of the use of trailers was insufficient crane capacity, resulting in decreased efficiency when operating at the required, full crane reach during trailer loading and unloading (Eriksson 1998); whereas technical developments have resulted in more powerful cranes (Nordfjell et al. 2010). Some trailer solutions are already available on the market in both the Northern and Southern hemispheres (for example, Timbear Lightlogg C (Timbear 2011) and Bell's long range forwarders (Bell 2010), respectively). New inventions also circumvent the need to work at long crane reaches, by having a trailer reversing parallel with the forwarder during loading, powered by the forwarder engine (Volungholen 2008). Thus, there are both environmental and technical reasons to re-evaluate the forwarder-trailer concept.

The objective of the study was to analyze the potential benefits of forwarder trailers in terms of time consumption, cost-efficiency, and fuel consumption compared to conventional forwarders, with and without axle load restrictions. The restrictions were motivated by the assumption that increased axle loads may increase soil damage (Håkansson 1994, Jansson and Johansson 1998), and that environmental concerns might eventually result in such restrictions. Thus, our evaluation addresses whether or not it would be more efficient to just reduce payloads on normal forwarders, or to use forwarder trailers. However, the restrictions are complementing and motivating the analysis, but to fully evaluate the possible machine-soil interactions when using a forwarder trailer is not within the scope of the study. The analyses were conducted by use of theoretical modelling to identify stand conditions in which the use of trailers may be viable compared with conventional forwarders in final felling. Moreover, the abundance of Swedish final fellings with favorable conditions for forwarder trailers was assessed.

2. Materials and methods

To fully evaluate the impact of the examined forwarding concepts, two general assumptions were made concerning the similarity of concepts. First, it was assumed that the outcomes of work were identical in terms of effect on the roundwood transported and unloaded at roadside landings. However, the impact on stand environment (for example, rutting and soil compaction) might vary, but is only taken into account here in terms of analyzing various measures to decrease axle loads. Second, it was assumed that it generally takes the same amount of time for the same type of work, but when differences are expected the employed methodology allows the parameters to be adjusted appropriately.

Aggregated machine time-consumption functions are first presented for productive machine (PM) time in minutes per produced solid m^3 of roundwood under bark (PMmin m^{-3}), which is defined as the delay-free machine time that directly contributes to the completion of the intended work task (cf. Björheden 1991). Then, the level of technical utilization is included, giving the time consumption per scheduled machine (SM) time in minutes per produced m^3 (SMmin m^{-3}). Finally, costs per m^3 are calculated based on scheduled-machine time-consumption. Costs were calculated in Swedish crowns (SEK), and converted to euros (€) using an average exchange rate of 10 SEK=1 € during 2010 (Sweden's Central Bank 2011). 1 m^3 of wood was assumed to have a mass of 900 kg.

2.1 Machine combinations and scenarios

All forwarders included in the study were assumed to be eight-wheelers, with tracks on all four bogies. The trailer was four-wheeled, with tracks on both bogies. In the comparisons, we assumed that the forwarder trailer was combined with a medium-sized forwarder with a reduced payload. The performance of that combination was compared with the performance of medium-sized and large forwarders with full payload and reduced payload, respectively, resulting in five different machine combinations in our study. Details of the combinations are presented below.

To include uncertainties in the cost and performance of a forwarder trailer, four scenarios were evaluated to cover the expected speed and price ranges. For time consumption, the fast scenario assumed that the use of a trailer increased the time required for all of the medium forwarder work elements by 5%. In the slow scenario, the use of a trailer was assumed to require 10% more time, plus an additional extra PM minute per load to account for eventual arrangements required for the loading and unloading of the trailer (for example, turning the trailer (Volungholen 2008) or adjusting the distance between the trailer and forwarder). In the cheap trailer price scenario, it was assumed that the trailer price was 30,000€ (10% of the cost of a medium forwarder), whereas a trailer in the expensive scenario was assumed to cost 70,000 € (23.3% of a medium-sized forwarder). Altogether, the scenarios were: fast-cheap, fast-expensive, slow-cheap, and slow-expensive.

Thus, in total the four forwarder trailer scenarios were compared with the four normal forwarder combinations.

2.2 Estimation of time consumption

Total forwarding time-consumption for a given machine was computed as:

$$T_{\mathrm{Total}} = T_{\mathrm{Driving,Empty}} + T_{\mathrm{Driving,Full}} + T_{\mathrm{Loading}} + T_{\mathrm{Driving,Loading}} + T_{\mathrm{Unloading}} \quad , PMmin\ m^{-3} \quad (1)$$

where:

- $T_{\mathrm{Driving,\ Empty}}$ time consumption of pure driving when empty (that is, from roadside landing and until loading starts),
- $T_{\mathrm{Driving,\ Full}}$ pure driving with full payload,
- T_{Loading} loading time,
- $T_{\mathrm{Driving,\ Loading}}$ pure driving when loading, and
- $T_{\mathrm{Unloading}}$ unloading time.

Time consumption for the work elements was based on equations provided by Nurminen et al. (2006) for loads with several assortments:

$$T_{\mathrm{Dirving,Empty}} = \frac{Max\left(0, d_{\mathrm{m}} - \dfrac{V_{\mathrm{F}} \times l_{\mathrm{r}}}{2V_{\mathrm{R}}}\right)}{v_{\mathrm{E}} \times V_{\mathrm{F}}} \quad , PMmin\ m^{-3} \quad (2)$$

$$T_{\mathrm{Dirving,Full}} = \frac{Max\left(0, d_{\mathrm{m}} - \dfrac{V_{\mathrm{F}} \times l_{\mathrm{r}}}{2V_{\mathrm{R}}}\right)}{v_{\mathrm{F}} \times V_{\mathrm{F}}} \quad , PMmin\ m^{-3} \quad (3)$$

$$T_{\mathrm{Dirving,Loading}} = \frac{l_{\mathrm{r}}}{v_{\mathrm{L}} \quad V_{\mathrm{R}}} \quad , PMmin\ m^{-3} (4)$$

$$T_{\mathrm{Loading}} = 1 + \frac{0.155}{Exp\left(-0.447 + 0.3 \times Ln\left(\dfrac{100V_{\mathrm{R}}}{l_{\mathrm{r}}}\right)\right)_{\mathrm{F}}} \quad PMmin\ m^{-3} \quad (5)$$

where:

- V_{R} abundance of loaded assortment(s), $\mathrm{m^3\ ha^{-1}}$,
- l_{r} total length of strip road network, $\mathrm{m\ ha^{-1}}$,
- V_{F} (full) forwarder load volume (payload),
- v_{E} average speed when driving empty, $\mathrm{m\ min^{-1}}$,
- v_{F} average speed when driving full, $\mathrm{m\ min^{-1}}$,
- v_{L} average speed while loading, $\mathrm{m\ min^{-1}}$,
- d_{m} mean extraction distance one way, m.

The total strip-road length (l_{r}) was set to 769 m, based on the assumption that there would be 13 m between roads in final felling (cf. Nurminen et al. 2006). It was assumed that all assortments were loaded together, and thus, V_{R} was equal to the stand density. Moreover, it was assumed that the distance driven loaded was equal to the distance driven unloaded. Given the assumptions, the distances driven full and unloaded could be estimated to be negative for small values of V_{R} and d_{m}, and for large values of V_{F}; hence, the use of the max function in equations 2 and 3.

In practice, $T_{\mathrm{Unloading}}$ varies depending on the mixture of assortments in loads. Although loads of different mixtures can be created, load mixtures were here assumed to be identical for all machine combinations. $T_{\mathrm{Unloading}}$ was set to 0.657 PMmin $\mathrm{m^{-3}}$; the highest mean value in the range, 0.547–0.657 PMmin $\mathrm{m^{-3}}$, suggested by Nurminen et al. (2006).

For the medium-sized forwarder, v_{E}, v_{F}, v_{L}, and $T_{\mathrm{Unloading}}$ were set to 56 m $\mathrm{min^{-1}}$, 44 m $\mathrm{min^{-1}}$, 27 m $\mathrm{min^{-1}}$, and 0.657 PMmin $\mathrm{m^{-3}}$, respectively (cf. Nurminen et al. 2006). To accommodate for larger engine and grapple, the large forwarder was assumed to be slightly faster, with the corresponding driving speed values being set to 58 m $\mathrm{min^{-1}}$, 46 m $\mathrm{min^{-1}}$, and 27 m $\mathrm{min^{-1}}$, respectively, while T_{Loading} and $T_{\mathrm{Unloading}}$ were taken to be 5% less than for the medium-sized forwarder.

Technical utilization was set to 90% for all machine combinations, that is, PM-time was transformed to SM-time by dividing it by 0.9.

It was assumed that the reduction of payload did not affect the time consumption per m^3.

2.3 Costs

Fixed costs for the machines were calculated according to Miyata (1980), applying the straight line method of depreciation and an approximate annuity method for interest. For all machine combinations, the interest rate was set to 6.5%, the expected service life was set to 6 years with 2600 scheduled hours per year, and the salvage value was taken to be 10% of the purchase cost. The labor cost was set to 37.8 € SMh^{-1}. Operating costs excluding fuel were set to 13.0 and 14.3 € SMh^{-1} for the medium-sized and large forwarder, respectively. The fuel cost was set to 1.1 € per liter and the hourly cost for fuel depended on fuel consumption (and hence on the engine size, see section 2.4). The total hourly costs for the machine combinations are given in Table 1.

Table 1 Costs for the machine sizes and the trailer combination scenarios

Forwarder combination	Purchase cost	Hourly cost
	10^3 €	€ SMh^{-1}
Large	500	95.84
Medium	400	85.55
Medium+trailer		
Cheap	430	88.46
Expensive	470	91.39

2.4 Fuel consumption

It was assumed that, owing to the hydrostatic-mechanical transmission of forwarders, each engine would work at a given number of revolutions per minute, with the forwarder speed reduced for heavier loads. Thus, the fuel consumption was estimated as:

$$C = 0.046W + 7.222\text{ , l PMh}^{-1} \tag{6}$$

where C is the fuel consumption and W is the engine output power in kW (Klvac and Skoupy 2009). The reduction of loads was assumed not to change the fuel consumption, whereas the use of a trailer was assumed to increase the fuel consumption by 5%. The estimated fuel consumption is shown in Table 2.

2.5 Axle load and ground pressure

For each axle of a machine combination, the axle load was calculated based on the machine mass and the number of axles to distribute the load on. It was assumed that 40% of the mass was on the front axle when a forwarder was loaded. Valmet 860 and 890 (Komatsu Forest, Umeå, Sweden) were used as model machines for the calculations, and they were assumed to be equipped with 0.81 m wide ECO-Track bogie tracks (Olofsfors AB, Olofsfors, Sweden) each weighing 895 kg. The trailer was assumed to have a mass of 7 t including bogie tracks, and being loaded with 9.5 t. The calculated axle load pressures are presented in Table 2. To give a rough estimate of the ground pressure, the axle load can be divided by area covered by the axle bogie bands (ca. 1.2 m^2 for each of the two bogie bands on an axle). The restriction on the medium sized forwarder axle loads were set to approximately reflect ground pressures of maximum 70 MPa (Wästerlund 1992). However, if the large forwarder should meet the same restriction, it should have a payload of only 8 t (44% of full payload). This

Table 2 Machine parameters

Forwarder combination	Acronym	Engine output power	Fuel consump-tion	Mass, t		Ratio of payload to unloaded	Axle load, t		
		kW	l PMh^{-1}	Total	Payload	mass	Front	Back	Trailer
Large	L	190	16.0	38.0	18.0	0.90	15.2	22.8	–
Large – reduced	LR	190	16.0	33.0	13.0	0.65	13.2	19.8	–
Medium	M	150	14.2	31.0	14.0	0.82	12.4	18.6	–
Medium reduced	MR	150	14.2	28.9	11.9	0.70	11.6	17.3	–
Medium reduced+trailer	MRT	150	14.9	45.4	21.4	0.89	11.6	17.3	16.5

was considered unrealistic, so its restriction was set to reflect ground pressures of maximum 80 MPa.

2.6 Stand data

Follow-up data for finally felled stands harvested by conventional systems were gathered from forestry companies for three regions of Sweden: Northern (Norrbotten, ca. 66° N, 22° E), Central (Medelpad, ca. 62° N, 16° E), and Southern (Östergötland-Sörmland, ca. 58° N, 16° E). For each stand, these data included information on the stand volume (m^3), stand density (m^3 ha^{-1}), mean harvested stem size (m^3), and mean extraction distance one way (m) (Table 3). The time-consumption functions used here were not adapted to stands with densities less than 100 and more than 1,000 m^3 ha^{-1}, and such stands were therefore excluded. This resulted in the exclusion of 7.5% of the harvested volume from the pooled, original data. Stands with more than 1,000 m^3 ha^{-1} corresponded to 0.6% of the pooled data and only occurred in the Southern dataset. The dataset used contained ca. 1.6 million m^3.

2.7 Data analysis

A deterministic, spreadsheet based model was constructed based on the abovementioned equations and assumptions for time and fuel consumptions as well as costs. In the analysis of favorable conditions, the model was used to systematically investigate the effects of various levels of extraction distances, stand volumes and stand densities. Subsequently, the model was applied to the stand data set, in order to investigate the abundance of favorable conditions. Thus, the former step aimed at finding the conditions where the forwarder trailer should be competitive. The latter step indicated how common such trailer favorable conditions were, based on a large sample of conditions occurring in Sweden.

Table 3 Characteristics of 1 129 stands (containing 1 624 004 m^3) included in the follow-up dataset of Swedish final fellings

Variable	Volume-weighted mean	Range
Mean stem size, m^3	0.41	0.05–2.78
Mean extraction distance, m	389	20–1500
Mean stand density, m^3 ha^{-1}	250	100–952

3. Results

3.1 Favorable conditions

Compared to the extraction distance, the stand density had only minor effects on the time and fuel consumption of the machine combinations. The effects were largest at small stand densities; the time consumption per m^3 was ca. 5–6% higher with a density of 50 m^3 ha^{-1} than with a density of 100 m^3 ha^{-1}, and

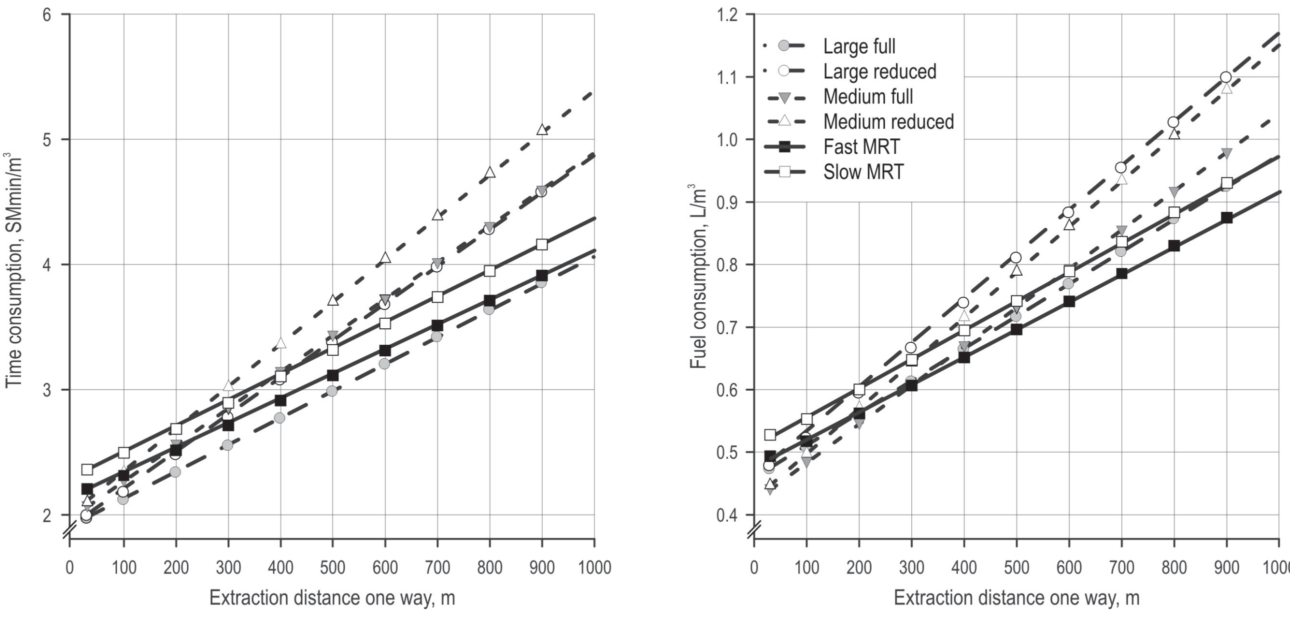

Fig. 1 Time (left panel) and fuel consumption (right panel) in final fellings (at 250 m^3 ha^{-1}) as a function of extraction distance for two payload scenarios, for large and medium-sized conventional forwarders, and for the forwarder-trailer combination (MRT) in the two speed scenarios

was 5–6% higher at 100 m^3 ha^{-1} than at 500 m^3 ha^{-1} (data not shown). Looking at costs, the effects were even less distinguishable. For instance, the distance at which it was equally expensive to use the trailer combination as it was to use the fully loaded large forwarder only marginally varied over densities from 50 m^3 ha^{-1} to 500 m^3 ha^{-1} (the break-even distance was between 750 and 760 m; data not shown). Thus, further analyses of favorable conditions focused on the influence of extraction distance at a given stand density (namely, 250 m^3 ha^{-1}, that is, the mean of the stand data).

As could be expected, the longer the extraction distance, the more time and fuel were consumed and the higher the costs were (Figs. 1 and 2). The fully loaded medium-sized forwarder was cheaper than both the large forwarder and all trailer scenarios at distances shorter than ca. 200 m but was more expensive at distances longer than ca. 650 m (Fig. 2). The large forwarder was cheaper than the fast-cheap trailer scenario only at short distances (less than ca. 150 m) whereas it was cheaper than the slow-expensive trailer scenario for all tested distances. The costs of the payload-reduced forwarders were very close to each other, and were less than those of all trailer scenarios for distances less than ca. 80–150 m but the payload-reduced forwarders were more expensive for distances longer than 300–400 m.

3.2 Abundance of favourable conditions

The proportion of the final-felling volume for which the trailer combination was cheaper to use than the conventional forwarders varied considerably across the speed-price scenarios; from 10 to 79% and from 0 to 98% for the medium-sized and large fully loaded forwarders, respectively (Fig. 3).

The variation across speed-price scenarios persisted for the payload-reduced forwarders but was somewhat less dramatic; the trailer combination was cheaper than the medium-sized forwarder for at least 52% of the volume, and for at least 78% of the volume when compared to the large forwarder (Fig. 3).

On the total volume of final fellings, the fast-trailer combination was always cheaper to use than a conventional forwarder with either a full or reduced payload, irrespective of trailer cost (Fig. 4). In the slow scenario, the trailer was at least 6.4% more expensive to use than the conventional, fully loaded forwarders. Compared to a fully loaded conventional forwarder, the trailer combination generally consumed less time and fuel (up to 8% less), except for in the slow scenario, in which fuel consumption was 3% higher. Conversely, the trailer combination generally consumed more time and fuel (up to 11.6% more) than a fully loaded large forwarder, except in the fast scenario, in which fuel consumption was decreased by 2.5%.

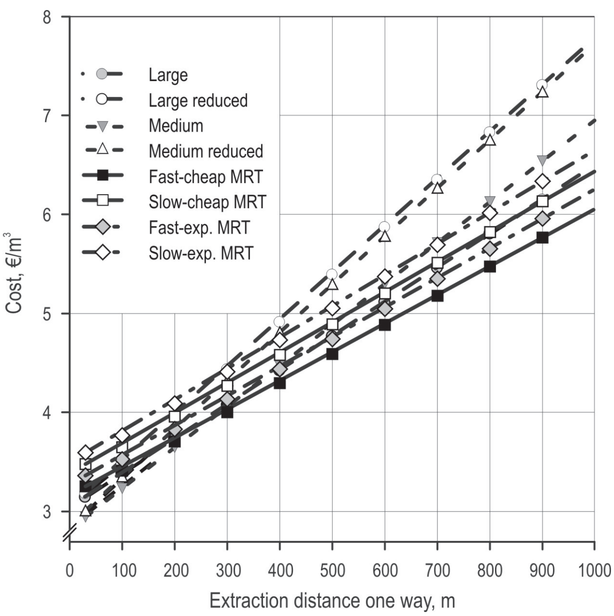

Fig. 2 Forwarding cost for final fellings (250 m^3 ha^{-1}) as a function of one way distance for the four conventional forwarder-payload scenarios and the four forwarder-trailer (MRT) speed-cost scenarios (exp.=expensive)

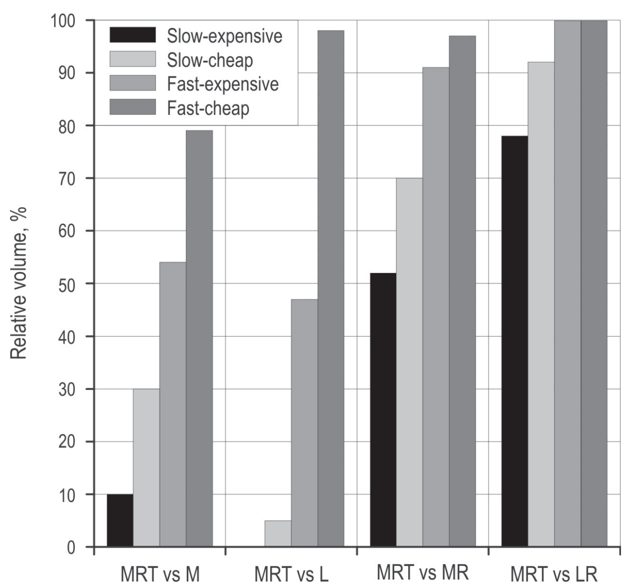

Fig. 3 Proportion of total final-felling volume in four speed-price scenarios for which the forwarder-trailer combination (MRT) was cheaper to use than each of the four conventional forwarder-payload scenarios (M/MR=medium-sized forwarder with full/reduced payload; L/LR=large forwarder with full/reduced payload)

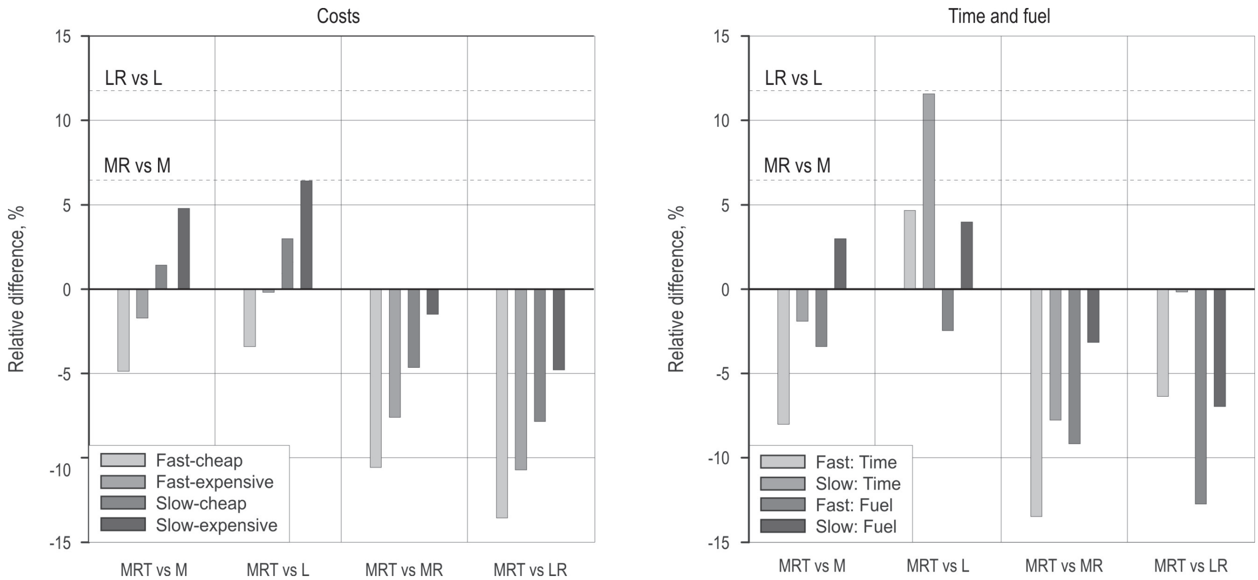

Fig. 4 Relative differences in costs (across speed-price scenarios, left panel) and consumption of time and fuel (across speed scenarios, right panel) between the forwarder-trailer combination (MRT) and conventional forwarder combinations when applied to the total final-felling volume. Negative values indicate that MRT was cheaper or less time- or fuel-consuming. Horizontal lines indicate the increased levels caused by payload reduction on conventional forwarders. M/MR=medium-sized forwarder with full/reduced payload; L/LR=large forwarder with full/reduced payload

In comparison with the payload-reduced conventional forwarders, all the trailer speed-price scenarios were viable in terms of lowering total costs (1.5–13.6% cheaper), time consumption (0.2–13.5% faster), and fuel consumption (a 3.2–12.7% reduction). Since costs and fuel consumption were directly dependent on time consumption for a conventional forwarder, the reduction in payload resulted in 6.4% higher costs, time, and fuel consumption than when using full payloads with the medium-sized forwarder. The corresponding increase was 11.8% for the large forwarder.

4. Discussion

4.1 Results

All together, there seems to be a substantial theoretical potential for the forwarder-trailer concept, especially so when restrictions on conventional forwarders axle load (that is, reduced payloads) apply. The cost of reducing axle load was considerably cheaper with the trailer combination (between 4.9% lower and 6.4% higher than the conventional cost) than when reducing the conventional forwarders payload (Fig. 4). In half of the speed-cost scenarios, the use of a trailer combination resulted in reduction of both axle load and costs, even when compared to fully loaded conventional forwarders (Fig. 4). However, the analysis indicates that the level of increased purchase costs and work-element time-consumption are crucial for the trailer concept viability when competing with conventional full-payload forwarders. Apparently, even rather small alterations in these levels result in large changes in the viability (for example, in the abundance of suitable conditions, Fig. 3). In the scenarios considered here, the time-consumption increase (fast vs. slow) was more influential than the purchase cost (cheap vs. expensive).

The current results agree with previous field studies (Eriksson 1998) in which a trailer combination was viable for extraction distances longer than 300 m under the assumption that the trailer only resulted in a higher hourly cost but not in increased time-consumption. When the observed increased time requirements were included in the calculation, the distance had to be at least 850 m for the trailer to be viable. The studies differ in terms of hourly costs for the trailer, since Eriksson (1998) assumed that the trailer would be used for only 50% of the work time (implying a higher fixed cost), whereas here it was assumed that the trailer would be used throughout the work time. However, assuming that the trailer is easy to attach and detach, it would be possible to use the trailer only on the most suitable harvesting sites. Indeed, the forwarder trailer combination would have the same hourly fixed cost irrespective of whether or not the trailer was used, but would have a lower fuel cost and allow faster work. An intelligent selection of where to use the trailer, and where not, could slightly improve the trailer combination viability. The estimation of such breakpoints was beyond the scope of this study, but would be of interest in studies based on empirical data.

4.2 Strengths and weaknesses of the study

In the methodology applied, the principal differences between forwarder combinations were addressed theoretically. Hence, the risk of confounding the effects of differences with noise intrinsically present in field studies was avoided. For instance, the influence of variations in the work environment, technical maturity, and operator influences did not affect the analysis. Moreover, this kind of theoretical approach enables analysis of machine concepts even when they are merely ideas (e.g. Jundén et al. 2013). Thus, this kind of analysis is beneficial for technological development because it can be used for early evaluations of, and subsequent concentration of resources on, systems with the highest theoretical potentials (Lindroos 2012).

However, all theoretical analyses are intrinsically dependent on the constructed models and input data used. Clearly, it is important to rigorously construct logical, realistic theoretical models and carefully evaluate the influence of variations in input levels and assumptions. In this study, these requirements were met by basing the model on generic forwarding models, with appropriate adjustments, and by addressing various scenarios to cover the uncertainties in time consumption and prices. Moreover, time-consumption differences were mainly expressed in relation to each other. Hence, changes in variables that are likely to affect all systems were also changed accordingly. This should minimize the risks of confounding differences between machine combinations with those related to low quality of available input data for the combinations (for example, unrelated and, thus, unharmonized data).

In the analysis, it was assumed that all combinations load similarly (for example, the same number and proportion of assortments are used for each combination), although there is the possibility of using different load mixtures for the different load spaces. This would alter the work time for loading, driving while loading, and unloading, with a general trade-off in time saved between work related to loading and to unloading (Manner et al. 2013). Hence, estimating the effects of this would not be straightforward and, moreover, the number of load mixtures grows rapidly as the number of assortments increases. Thus, load mixtures were excluded here for the sake of simplicity, but should be of interest to address in future studies. However, it is most likely that the time-consumption scenarios used here do not favor the trailer.

One might argue that the increased payload volume should enable the trailer to take additional assortments and thereby decrease the loading time. However, despite the theoretical potential it is likely that there would be practical limitations in terms of crane capacity, as pointed out previously (Eriksson 1998). In practice, it might turn out that only small-sized wood (for example, pulpwood) could be loaded onto the trailer. Under the assumption that the trailer has to be loaded first, since loading the bunk first would severely impede on the visibility in trailer loading, the practical loading possibilities might be considerably reduced and this was therefore not addressed here.

Additional possible practical limitations that were not considered here are whether or not the conventional forwarders have to be modified in order to be capable of pulling the trailer. Although this might require only minor modifications, it is likely to increase the purchase cost. Although not specifically addressed here, the assumed increased price for the trailer combination includes the cost of the trailer and of the forwarder modifications, up to the price levels specified in the scenarios.

Even though the viability of the trailer combination was analyzed mainly for Nordic conditions, it is very likely that the relationships found between factors also apply under other conditions. However, the specific outcome in terms of favorable conditions and their abundance is intrinsically site-specific and would have to be assessed for any given location under consideration. Thus, future studies should focus on analysis at an enhanced level of detail and/or applications and under other environmental settings. The trailer combination might, for instance, be of interest in the recovery of logging residues. It would also be of interest to go forward with field studies to gather contemporary empirical data on costs and time consumption. Some trailer prototypes are already in use in Sweden, and will be subject to field studies.

5. Conclusions

Based on this theoretical analysis, it can be concluded that there are potential economic and possibly also environmental benefits that warrant further investigation of the forwarder-trailer concept. Prototypes are already being tested in practice, which will contribute to such investigations by providing empirical data on practical limitations and actual costs and time-consumption.

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Authors' address:

Assoc. Prof. Ola Lindroos, PhD.*
e-mail: ola.lindroos@slu.se
Department of Forest Biomaterials and Technology
Swedish University of Agricultural Sciences
90183 Umeå
SWEDEN

Prof. Iwän Wasterlund, PhD.
e-mail: iwanolasgarden@telia.com
Olasgarden Forest and Roads
Solvägen 9
91832 Sävar
SWEDEN

* Corresponding author