

## Research Article

# Road Transport Vehicles for Hauling Uncommminated Forest Energy Products in Sweden

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Forestry residues as a renewable energy source are becoming increasingly competitive to fossil fuels. An important issue, however, is effective transportation solutions for this type of material. In this paper we describe and discuss several alternative vehicle systems which have been used in Sweden. We describe and discuss a specialized vehicle for the transportation of loose residues, bundled residues, and tree sections; a specialized stump hauling vehicle; a recently developed vehicle for the transportation of bundled residues; a container system vehicle for stump transportation. All these different machineries have their merits and shortcomings depending on the type of forest energy product.

## 1. Introduction

Concerns regarding climate change and global warming [1, 2] have led to ambitious goals of reducing greenhouse gases due to use of fossil fuels [3, 4]. Many countries have adopted strong policies to reduce harmful emissions. These policies are often implemented by imposing higher taxes on fossil fuels which increase fossil fuel prices relative to alternative energy sources. As a consequence renewable energy sources in general and forest energy products in particular have become increasingly more demanded [5]. In Sweden for instance many central heating and power plants use some sort of forest energy product as input to produce heat or power. According to the Swedish District Heating Association [6], biomass, including processed and unprocessed forest energy products, accounted for almost 50% of the input material for heat production in 2008, a 120% increase from 1996.

An important issue, and the one this paper is occupied with, is the logistics involved in the process from harvesting to transportation of the forest energy products to the final user. Forest energy products come in various forms, for example, as residue products from clear cuttings, small trees [7], or stumps [8]. The raw material can be processed in a number of

ways before road transport such as wood chips, tree sections, and loose and bundled residues [9–13].

Compared to fossil fuels, forest energy products have lower energy density, which implies that a larger mass must be transported to produce the same amount of heat or power [14]. Moreover, forest energy products can be harvested in many different locations in the forests as compared to fossil fuels which usually have a main extraction point. For the latter, standardized transportation modes, for example, pipelines and trains, can be used while use of trucks, at least initially, is unavoidable for transporting forest energy products.

What is the most suitable way of transportation will depend on the type of forest energy product, quantity, the final user's activities and preferences, distance, and other circumstances. Transportation also involves negative external effects on the general population and the environment, for example, accidents or air pollution, and thereby social costs [15].

Logistics regarding forestry energy products has been studied and developed for some time now. Already in the early 1980s a study was conducted on how to transport undelimbed tree sections with conventional forest trucks [9].

The truck sides and floor were covered with planks, and a log in the grapple was used to compress the material (Figure 1(a)). There was an opening in the sides making it easier to unload the vehicle, which in this case was done with a Pettibone Carry Lift (Figure 1(b)). Forwarding was done with a conventional forwarder for round wood modified for the energy material (Figure 1(c)). Figure 1(d) shows a truck equipped with a chipper for roadside chipping. The transportation of the chips with this truck to a heating plant was studied in 1989 [16]. This system was also tested (on suitable sites) for forwarding tree sections with a forwarder equipped with articulated stakes for compression (Figure 1(e)).

One way to increase productivity is to compress the material. Compressing logging residues was studied by [17] as a test for small-scale forestry (Figure 1(f)). A prototype equipped with compressing details—the Tracobi Press (Figure 1(g))—was also tested but was found to be too heavy [18]. Nordén [19] reported that the solid volume for logging residues during transport was in the range of 15–20% loose volume ( $1\text{ m}^3$  logging residues loose volume equal to  $0.15\text{--}0.20\text{ m}^3$  solid volume) compared to 60–70% for pulpwood. For tree sections the solid volume was approximately 25–35% of loose volume. He also carried out a study where the compressing was done by a self-loading truck (crane) as well as a separate loader. Compression increased productivity and transport costs were thereby estimated to be reduced by 10–20%. Technology was also developed whereby the load (if wood chips) could be tipped sideways [20]. This technology is still used for transportation of, for example, loose residues, bundles, and tree sections.

Studies were also made on single compressing units for tree sections which were attached to trucks for road transport [21, 22]. The single compressing units were used mainly for testing purposes. The test truck for logging residues—the Tracobi Press—was also tested for tree sections [23] as was another test truck for tree sections “Hydrovåg” (Figure 1(h1) and (h2)). Neither of these methods had, however, any success.

A third method—ExTe Comp—(Figure 1(i)) was involved using hydraulically controlled stakes and throw-over laths to pull the stacks together [23]. That method was not further developed for the transportation of forest energy products but was further developed for security and ergonomic reasons when transporting round wood (Figure 1(j)).

An alternative method for handling fuel chips was studied where the chipping was done in the forest (or from stacks) and then the chips were tipped onto tarpaulins at the roadside (Figure 1(k)). The loading was done with a crane and a bucket ( $1.6\text{ m}^3$ ) mounted on a self-loading truck (Figure 1(l)) which was unloaded by side tipping the loads on truck and trailer [10]. This method was found to be more independent of, for example, loading machines; however, dirt could easily contaminate the wood chips.

A more traditional system was the container system (Figure 1(m)) where chipping was done in the forest (Figure 1(n)) or from a stack and then was transported to landing area and tipped into containers (Figure 1(o)) for final

transportation to the customer. However, the self-loading vehicle did not show any lower time consumption in comparison with the traditional system [10]. This study also confirmed that the container system was a rather sensitive system, for example, due to narrow time margins, which made transport planning difficult.

Engblom [24] suggested that in transport development the highest priority should be given to activities early in the logistic chain, such as forwarding, terminal work, and train transportation. Näslund [12] found, on the other hand, that the transportation of bundles was much cheaper than for loose residues but that the cost for bundling was so high that the bundling activity might be called into question. In cost calculations by Johansson [25] it was shown that in the case of dried material it was difficult to obtain a full load. With material drier than 40–45% moisture content it was not possible to obtain a full payload.

## 2. Cases of Road Transportation of Forest Energy Products in Sweden

In this section different cases of road transportation of forest energy products in forms of loose residues, bundled residues, tree sections, and stumps are described. The residues were from forest harvesting operations. The bundled residues were on average 3.1 meters long. The tree sections were either small trees or tree fragments being maximum 5.1 meters long. The stumps were dismembered. The vehicles used to transport these assortments were a specialized vehicle (denoted as specialized vehicle 1) for transportation of loose residues, bundles, and tree sections, a specialized stump hauling vehicle (denoted as specialized vehicle 2), a recently developed vehicle for transportation of bundles (denoted as specialized vehicle for bundles), and a container system vehicle for stump transportation (denoted as container system vehicle). The transports took place in the three centrally located counties: Värmland, Dalarna, and Gävleborg in Sweden, both under summer and winter periods. The roads were mostly gravel.

Two of the vehicles, specialized vehicles 1 and 2, respectively, were “normal self-loading round wood vehicles.” Number 1 (Figure 1(p)) was modified with metal covered sides and floor and some other details such as a crane (with a reach of 10.9 m) and a grapple which was adapted to handle logging residues. The wheel base on the trailer could be shortened by pulling the rear bogie forward and thus improve maneuverability in narrow passages. The rear bunks (and floor) on the trailer could be pulled forward when loading and then the bunks and the stack were pulled back again after loading. The top of the trailer (rear half) was covered with a roof and a lid (front half) which could be opened when loading. This vehicle was used for the transportation of loose residues, bundles, and tree sections. The crane was used for unloading. The total permitted weight of the vehicle was 60 tonnes and the payload was approximately 26.3 tonnes depending on the amount of snow and dirt on the vehicle. The maximum load volume was  $148\text{ m}^3$ .

Specialized vehicle 2 (Figure 1(q)) was modified with metal covered sides and floor and some other details such as a

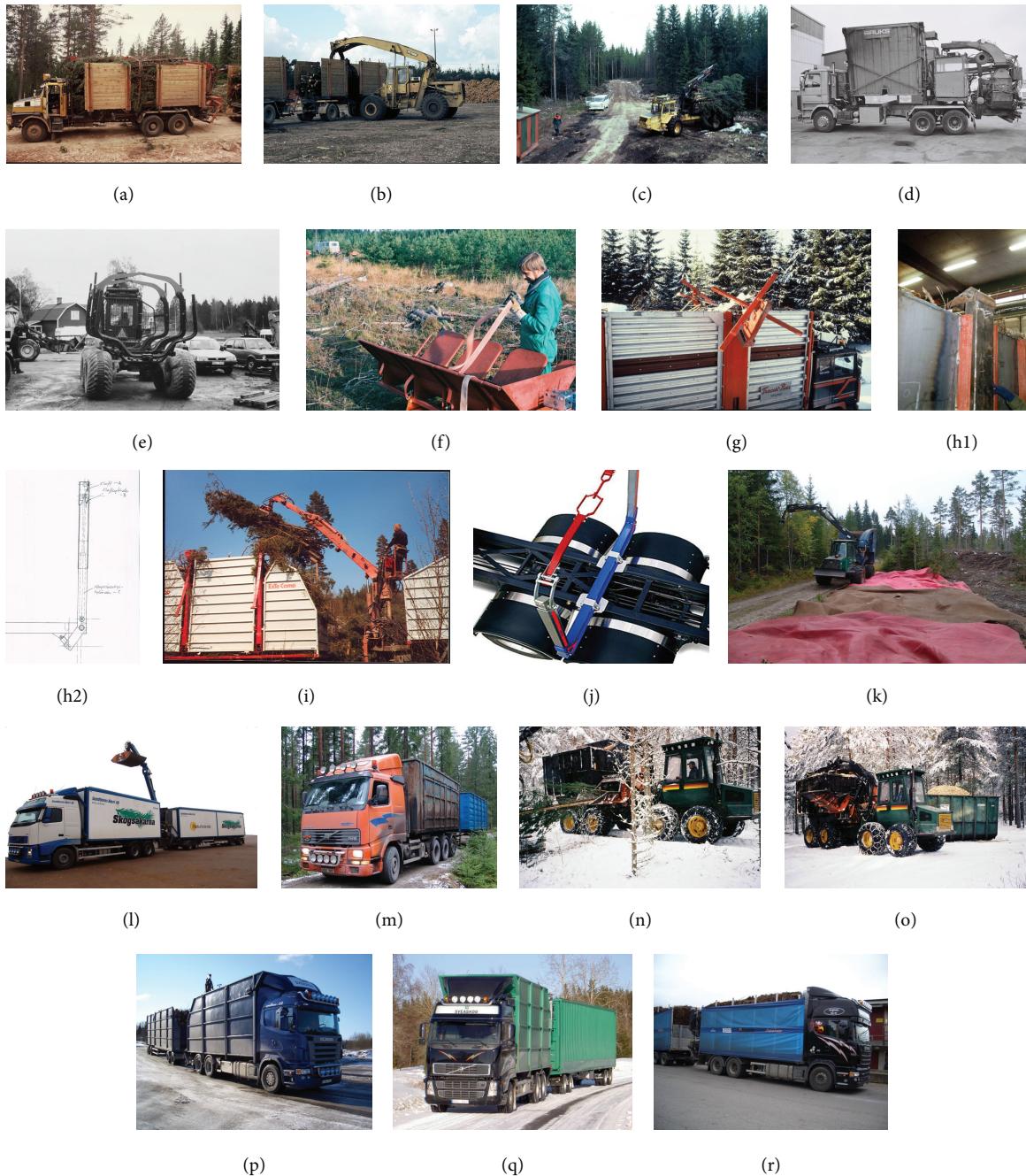


FIGURE 1: (a) Test truck for transport of tree sections with sides and floor being covered with planks. (b) Unloading tree sections at terminal with Pettibone Carry Lift. (c) Forwarding tree sections. (d) Truck with an integrated wood chipper for chipping at road side. (e) A forwarder with articulated stakes for compression. (f) Compressing unit for bundles in private forestry. (g) The Tracobi Press. (h1) The Hydровäg truck for compressing and transporting tree sections. (h2) Principles for compressing with the Hydровäg truck (early drawing, A = flap, B = cylinder for manoeuvring the flap, C = cylinder for compressing). (i) The ExTe Comp tested for compressing and transport of tree sections. (j) The ExTe Comp system (Com 90) used for safety and ergonomic reasons when transporting round wood. (k) Tarpaulins on the ground for fuel chips. (l) Self-loading truck with a bucket for transport of wood chips from road side/landing. (m) Traditional container system (here with 2 bins). (n) Chipping in the stand. (o) Transport to landing and then filling transport container with fuel chips. (p) The specialized vehicle 1 observed in the time study. (q) The specialized vehicle 2 observed in the time study. (r) Specialized vehicle for bundled loose residues observed in the time study.

crane (with a reach of 9.6 m) and a grapple modified to handle logging residues. When loading the trailer it was first loaded in the front and then the stack was pushed backwards to the rear. Unloading the truck was done with the crane. The trailer was unloaded by "skimming" the top with the crane and then pushing the rest backwards through the rear doors. The total permitted weight of the vehicle was 60 tonnes and the payload was approximately 27.1 tonnes depending on the amount of snow and dirt on the vehicle. The maximum load volume was 145 m<sup>3</sup>. This vehicle was used to transport stumps during the study period.

The specialized vehicle for bundles was a recently developed prototype for the transportation of bundles. The sides and floor were covered with a net to protect traffic from loose particles (Figure 1(r)). The total weight permitted was 60 tonnes, the payload was approximately 35.7 tonnes, and the vehicle was self-loading with a crane mounted on the truck.

The container system vehicle was a self-loading "container system" with three bins, one on the truck (35 m<sup>3</sup>) and two on the trailer (2 × 38 m<sup>3</sup>). This vehicle was used to transport stumps. The trailer was not equipped with a tipping device. The total weight permitted was 60 tonnes and the payload was approximately 27.4 tonnes. The crane reach was 7 m and the grapple was a standard grapple for round wood. When loading or unloading, the truck and the trailer had to be disconnected from each other. The bins on the trailer also had to be placed on the truck to make it possible to tip.

The forest energy products had been harvested 1-2 years previously and then put in stacks to dry. Some of the stumps were harvested about 2-3 years ago. The moisture content decreases rather rapidly over time. Average moisture content for air-dried biomass is about 20% [26]. The observations were carried out over a 1.5-year period.

According to the owners declaration the investment levels for the vehicles were 490000€ and 510000€ for the specialized vehicles 1 and 2, respectively. Investment levels were 305000€ for the container system vehicle and 407000€ for the specialized vehicle for bundles.

Time consumption on different handling activities in connection to loading (in the forest) and unloading (at the end users' facilities) was measured. Handling activities were, for example, setup, weighing, crane work, compressing, and so forth (the appendix). Collected data from this time study were analyzed using the statistical package Stata [27]. The measurements are based on observations on four forest energy products transported by different vehicles. It is important to note that the observations were not based on an experimental design but on actual operations. Only one vehicle, the specialized vehicle 1, was used for transporting several types of energy products, namely, loose residues, bundles, and tree sections. This limits the scope for a detailed comparison across energy products and vehicle types. The other vehicles were used to transport only one assortment each.

Loose residues were transported with the specialized vehicle 1. This vehicle had a load volume of 148 m<sup>3</sup> and a crane reach of 10.9 m. There were in total 21 loads observed. The

mean payloads 18.0 tonnes were with a standard deviation of 7.7. Minimum and maximum payloads were 6.1 and 28.9 tonnes, respectively.

Tree sections were transported only with the specialized vehicle 1 described earlier. There were 16 loads observed. The mean payload was 24.5 with a standard deviation of 5.9.

Stumps were transported by two different vehicles. The first vehicle that here is referred to as specialized vehicle 2 had a load volume of 145 m<sup>3</sup> and a crane reach of 9.6 m. The second vehicle, a self-loading container system vehicle with three bins, one on the truck (35 m<sup>3</sup>) and two on the trailer (2 × 38 m<sup>3</sup>), had a total volume of 111 m<sup>3</sup>. The crane reach for this vehicle was 7 m. There were 7 and 12 loads observed for the first and the second vehicles, respectively. The mean payloads were 18.9 and 18.0 tonnes with standard deviations of 1.2 and 3.7, respectively.

Bundles were transported with two different vehicles: the specialized vehicle 1 described earlier that was also used for transporting loose residues and a recently developed prototype especially for the carriage of bundles. The latter vehicle used a crane with a reach of 10.1 m. There were 17 and 10 loads observed for the first and the second vehicles, respectively. Mean payloads were 27.5 and 34.0 tonnes with standard deviations of 1.4 and 3.2, respectively.

Table 1 summarizes the payloads for the transports that were observed. The payloads obtained depend to a great extent on what assortment was transported. The largest mean payload was observed for bundles, probably because of the bigger compressed units. Tree sections have the next largest mean payload, also to some extent, depending on a relatively high percentage of stem wood making the load quite compact. The smallest mean payload for the specialized system was for loose residues.

The smallest mean payload among all cases was found for stumps in the container system vehicle. Stumps normally have a very high degree of solid wood but are on the other hand hard to compress. In addition, the volume of the bins was also smaller than for potential load volumes for the specialized vehicles (more than 30 m<sup>3</sup> less). During the study it was observed that with a higher degree of fragmentation it was easier to compress the stumps and thereby obtain more loads, something which had also been noted in earlier studies [28].

The mean time consumption for the different handling activities at terminal as a percentage of total handling time is presented in Table 2. In some cases the percentage for some activities does not vary to any higher degree between different forest energy products. However, given the higher total time consumption per load and tonne for some forest energy products, a rather similar percentage for some components means that their respective absolute values are higher.

Table 3 shows that loading and unloading time consumption at the terminal for the specialized vehicle 1 was least for bundles. Among all assortments, time consumption at the terminal was much higher for stumps. When time consumption per tonne is considered the results are approximately the same. Time consumption per tonne for loose residues is almost twice as high as for bundles and tree sections. For

TABLE 1: Number of observations and mean payload for each case.

Forest energy product	Loose residues	Tree sections		Stumps		Bundles	
Transportation mode	Specialized vehicle 1	Specialized vehicle 1	Specialized vehicle 2	Container system vehicle	Specialized vehicle 1	Specialized vehicle for bundles	
Total number of loads studied	21	16	7	12	17	10	
Mean payload in tonnes (SD)	18.0 (7.7)	24.5 (5.9)	18.9 (1.2)	17.9 (3.7)	27.5 (1.4)	34.0 (3.2)	

TABLE 2: Mean time consumption for specific handling activities in percentages.

Handling activity at terminal	Forest energy product	Loose residues	Tree sections		Stumps		Bundles	
	Transportation mode	Specialized vehicle 1	Specialized vehicle 1	Specialized vehicle 2	Container system vehicle	Specialized vehicle 1	Specialized vehicle for bundles	
Set-up time 1	6.44	7.82	5.81	9.42	9.47	8.76		
Set-up time 2	10.70	10.26	5.40	9.88	13.39	19.52		
Set-up time 3	4.06	4.18	6.74	5.38	4.90	7.58		
Crane work	52.99	52.36	56.46	32.57	49.98	48.61		
Weighing with load	14.26	13.86	9.46	4.76	11.66	9.50		
Pushing load out	—	—	5.46	—	—	—		
Weighing without load	5.68	5.01	5.02	1.85	4.01	2.64		
Mounted/dismounted crane	—	—	—	6.19	—	—		
Handling of bins (emptying)	—	—	—	15.13	—	—		
Compressing	—	—	3.76	9.88	—	0.34		
Moving	1.20	0.19	0.30	0.37	2.74	1.68		
Other	4.66	6.31	1.59	4.57	3.85	1.35		

Note: set-up time 1: the time from the moment the equipage stopped until the moment the crane started moving. Set-up time 2: the time from the moment the crane was parked until the equipage started moving. Set-up time 3: other stoppage times in the crane work.

TABLE 3: Mean time consumption in minutes per load and tonne (standard deviations in parentheses).

Activity	Forest energy product	Loose residues	Tree sections		Stumps		Bundles	
	Transportation mode	Specialized vehicle 1	Specialized vehicle 1	Specialized vehicle 2	Container system vehicle	Specialized vehicle 1	Specialized vehicle for bundles	
Loading, min/load	41.50 (15.19)	35.20 (7.56)	51.78 (2.99)	104.39 (15.51)	32.78 (26.93)	79.58 (10.44)		
Unloading, min/load	33.98 (7.34)	30.12 (5.93)	42.69 (5.38)	59.83 (4.49)	27.96 (4.47)	61.74 (7.11)		
Aggregate, min/load	75.48 (19.24)	65.32 (9.52)	94.47 (5.90)	164.22 (18.91)	60.73 (28.68)	141.32 (14.29)		
Loading, min/tonne	2.51 (0.86)	1.54 (0.51)	2.74 (0.21)	6.05 (1.65)	1.19 (0.94)	2.35 (0.27)		
Unloading, min/tonne	2.24 (0.99)	1.45 (1.06)	2.25 (0.21)	3.47 (0.84)	1.02 (0.18)	1.84 (0.30)		
Aggregate, min/tonne	4.75 (1.63)	2.99 (1.51)	5.00 (0.24)	9.52 (2.43)	2.21 (1.01)	4.19 (0.94)		
Number of observations	21	16	7	12	17	10		

TABLE 4: Comparison of the observed vehicles according to level of investment, load volume, load weight, and performance.

System	Investment	Permitted load volume	Permitted load weight	Performance <sup>a</sup>
Container system vehicle	1	1	1	1
Specialized vehicle 1	1.61	1.33	0.97	2.00–4.31 <sup>b</sup>
Specialized vehicle 2	1.68	1.31	0.99	1.90
Specialized vehicle for bundles	1.33	—	1.30	2.27

<sup>a</sup>Performance is defined as the relative total time consumption per tonne at the terminal.

<sup>b</sup>Depends on type of assortment (lowest performance for loose residues and highest performance for bundles).

stumps, time consumption is more than twice as high as for loose residues. For bundles and tree sections mean time consumption is about the same.

In Table 4 the observed vehicles are related based on four factors: investment, permitted load volume, permitted load weight, and performance which is measured as the total time consumption for the required handling at the terminal. Normalization is done by considering the container system vehicle as the base vehicle and giving it the weight one.

There are no major differences in load weight capacity while there are greater differences considering load volume capacity. This means that, for example, the vehicle with the largest volume also has the biggest potential to have a full load if the material transported is dried. What type of forest energy product is handled is also important. However, this does not automatically mean that the system with the highest performance should be used. It is also important to consider how the forest energy material is handled before and after road transport (including, e.g., forwarding, storing, bundling, and chipping).

### 3. Discussion

As indicated earlier in the paper there are various machineries in the market for handling and transporting forest energy material. There are still no standardized systems and each system is more or less unique. The vehicles presented here too differ from each other. Therefore, they should more be looked at as principles and alternative solutions. Each vehicle is also more or less a product of each truck owner's ideas and visions and if they fully can pay for the investments needed. Another important factor is that there must be material enough to transport and to an acceptable level making it possible to invest. The specialized vehicles are particularly developed for transportation of forest energy raw material, and the investment level is in two cases more than 60% higher than for the vehicle in the container system. That vehicle was based on a truck and bins which could be used in many other types of transportation as well. Mainly a forest crane with a grapple for handling (loading) round wood was added.

Depending on the investment levels and performance, for example, time consumption and other handling costs at terminal, the transport costs are different with respect to both vehicle and assortment. For instance, transport costs for bundles per unit distance are relatively lower not least due to bundles being more compressed. The observation that mass is the primary factor behind the transportation cost of forest energy products is also observed elsewhere [29]. Also transporting forest energy products is associated with high costs due to the vehicles' high tare weights. Generally, lower tare weight implies increased freight capacity [30]. This was especially observed in the performance of the prototype vehicle for bundles which has a relatively lower tare weight. Of course, transportation costs for forest energy products have implications for geographic localization of the industry and even heat or power plants.

### 4. Conclusion

Forestry residues are valuable energy sources that are being increasingly demanded. This research shows that because of the diversity of the raw material, there is not one standard road transportation system that is best for all cases. For instance, one of the vehicles described here is specially designed to transport residues in bundled form and naturally is most efficient given that the raw materials are first processed into bundles which requires additional resources. It was also found that transporting stumps with the specialized vehicle was more efficient in terms of terminal handling time than the container system. On the other hand, the specialized vehicles are more expensive and require a higher level of initial investment. Some already known facts have been confirmed; for example, higher payloads were achieved with more compressed material. However, to properly compare different transportation solutions and identify optimal ones there is a need for an experimental study design when different factors are controlled for.

## Appendix

### Elements in Time Study

Set-up time 1: the time from the moment the vehicle stops till the moment the crane starts moving (including separation of trailer from truck (container system vehicle)).

Set-up time 2: the time from the moment the crane is parked till the vehicle moves (including time for connection of container system vehicle).

Set-up time 3: other times for delay in crane work (e.g., cleansing of material).

Weighing: with and without load.

Crane work: time for crane work (loading/unloading).

Compressing: compressing of material (stumps and bundles).

Handling of bins (empty): container system vehicle.

Mounted/dismounted crane: container system vehicle.

Pushing load out: trailer specialized vehicle 2.

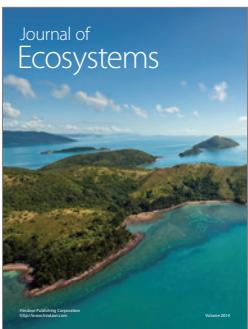
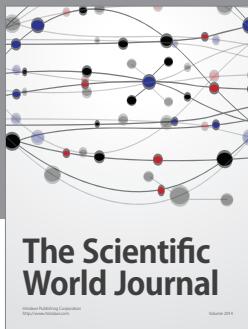
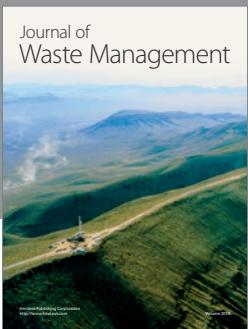
Moving: driving between stacks.

Others: for example, cleansing after unloading, moving stack on bunks back/forth, or opening/closing the lid.

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