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Energy Efficiency of Timber Transport by Trucks on Hilly and Mountainous Forest Roads

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Abstract

Timber transport by forest truck represents one of the largest energy consumers in the whole timber supply chain. Previous studies suggest that forest trucks spend as much as 14% of time driving on the primary forest roads, and that they consume a significant amount of energy in their total driving time. The fuel consumption is significantly impacted by the longitudinal slopes of the primary forest road network on which the timber is transported. This paper presents the results of research on fuel consumption by forest trucks while driving unloaded and loaded, depending on the longitudinal slope of forest roads. While driving an unloaded forest truck, increase in slope increases fuel consumption exponentially, and ranges from .7 L/km at an inclination of 3.5% to 1.6 L/km at an inclination of 9.5%. The fuel consumption of a loaded truck tends to increase exponentially with an increase of slope, and ranges from 1.21 L/km with 0% slope to 3 L/km with 8% slope. It can be concluded that a nominally loaded forest truck consumes on average 2.5 times more fuel on the same longitudinal slope in relation to the unloaded vehicle. The results show a strong link between fuel consumption and longitudinal slope. Carbon dioxide emissions are several times lower when the loaded forest truck is driven down the slope, when compared to being driven up the slope.

Keywords: CO₂ emission, forest truck, fuel consumption, longitudinal slope

Introduction

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Content of this journal is licensed under a Creative Commons Attribution-NonCommercial 4.0 International Long-distance timber transport by forest trucks is the final sub-phase of timber harvesting. Due to its characteristics, a cyclic operation, a large proportion of the distance driven being with an unloaded vehicle, the high cost of vehicle purchase, the transport of relatively small amounts of cheap goods, the high fuel prices and high fuel consumption, long-distance timber transport by forest trucks is characterized by extremely high costs. In addition to the high costs, long-distance timber transport by forest trucks has significant environmental impacts due to greenhouse gas (GHG) emissions and low energy efficiency (Ghaffariyan et al., 2018; Svenson & Fjeld, 2016). Malnar (2000) stated that long-distance timber transport by forest trucks is the most expensive form of timber transport and concluded the need for meaningful technical, technological, and organizational measures to reduce costs and environmental footprint. The energy demand for timber transport by a truck depends primarily on the distance covered, as well as on the other factors of travel speed, road surface conditions, etc. (Lijewski et al., 2017). Đuka et al. (2017) stated that slope is the second important factor that shows a nonlinear influence on energy consumption and GHG emissions. Increasing the slope to about 50% doubles the energy consumption and GHG emissions, while a slope of 70% almost triples them.

Today in Croatia, almost all wood products are transported by forest trucks. The reasons for this can be found in the development of forest trucks and truck transportation in general, the construction of such a network of public roads that allows the mass use of forest trucks, and the overall opening of forests by building primary forest roads (Horvat & Šušnjar, 2002).

A prerequisite for rational and sustainable forest management is a properly planned and built network of forest roads (Brinker & Tufts, 1995). Lepoglavec (2014) explored the importance and function of forest transport infrastructure and stated that the main role of forest roads is rational timber transport as well as transport of other (secondary) forest products from the forest stand. Forest transport infrastructure for the transport of timber comprises the primary forest traffic infrastructure for long-distance transport of timber, and the secondary forest traffic infrastructure constructed for timber extraction.

Berg and Lindholm (2005), Svenson (2011), and Klvač et al. (2013) cited a number of technical factors affecting the fuel consumption of forest trucks and therefore the emission of GHGs. The factors were classified into the following groups: vehicle features, features of trailers, road geometry, driving speed, gear changing, driving style, weather conditions, structure and conditions of the upper layer of forest roads, transportation distance, and organizational characteristics (driving unloaded vehicles while returning). Murphy (2003) and Favreau (2006) stated that in the total cost of long-distance timber transport by forest trucks, the cost of fuel accounts for 30%, while Svenson and Fjeld (2016) stated that transportation cost accounts for more than 25% of the forestry costs. Bandivadekar et al. (2008) stated that in order to reduce fuel consumption in the short term, more can be achieved by changing the style of driving than by improving vehicle characteristics or developing new synthetic fuels. By driving in optimal mode, significant savings in fuel consumption and emissions of exhaust gases can be achieved (Mercedes & Cervantes de Gotar, 2002).

Analyzing the road transportation of round wood with six trucks in Austria, Holzleitner et al. (2011) reported that when an average distance of 51 km (from 27 to 102 km) was driven, the average fuel consumption was .77 L/km (.32 L/km for unloaded trips and 1.02 L/km for loaded trips). Guimarães et al. (2016) analyzed fuel consumption of the forest truck and stated that it was .74 L/km (.53 L/km for unloaded trips and .78 L/km for loaded trips). They also stated that all phases of the trip (unloaded trip, loaded trip, and total cycle) presented a strong correlation between driving distance and fuel consumption, showing a direct relationship between them. This is expected, because distance is one of the main factors that contributes to the transportation cost. Bennamoun et al. (2017), in his research, assumed that driving above 50 km for transportation is not efficient.

Potočnik (1989) explored the influence of the longitudinal slope of forest roads on fuel consumption. He stated that forest trucks while driving downhill (-4%) used from 40% to 76% less fuel than driving on straight sections, and that driving uphill (+4%) increased fuel consumption from 53% to 83% compared to driving on straight sections of forest roads. Further, the author concluded that on the steepest parts of the forest traffic infrastructure network (slope +8%), fuel consumption was doubled. In his research, the author used a device for measuring fuel consumption, with an accuracy up to .1 L.

Kure (1990, 1992) measured fuel consumption with respect to the category and the slope of forest roads as well as during the loading and unloading of timber assortments. The author stated that the average fuel consumption was .67 L/km (.77 L/km while driving unloaded up the slope, or .57 L/km driving loaded down the slope). During driving uphill, the average fuel consumption amounted to 1.21 L/km, and driving downhill to .23 L/km, driving on roads without longitudinal slope and without horizontal curves consumed up to .62 L/km, while driving on roads with horizontal curves up to .61 L/km. The author also states that the fuel consumption when driving an empty forest truck was significantly higher due to the characteristics of transportation in the hilly area, where the timber is transported from the mountain into the valley. Fuel consumption while driving a loaded forest truck uphill with the increased number of revolutions per minute (RPM) (higher than the optimum amount), depending on speed ranged from 1.01 L/km to 2.61 L/km⁻ Devlin (2010), by equipping two haulage trucks (a timber haulage truck designed for the transport of timber on forest and public roads, and the second—a general haulage truck, designed solely for transport on public roads) with a system for collecting and sending data using a fleet management system (FMS), concluded that the forest haulage truck consumes twice as much fuel compared to a general haulage truck which drives solely on public roads.

Oberscheider et al. (2013), according to the numerical model representing the input parameters while driving and the fuel consumption of forest trucks, concluded that CO_2 emissions are higher on a fully loaded forest truck and that it significantly increases when the forest truck is driving at a speed less than 25 km/h.

Lijewski et al. (2017) determined the fuel consumption of forest trucks through the carbon balance method, according to the procedure adopted by the EPA (Environmental Protection Agency). The fuel consumption during the transport stage from the cutting site to the lumberyard was .73 L/m³.

The Croatian state-owned company, Croatian Forests Ltd., owned 259 forest trucks and in the year 1996 and was involved in 85% of the total long-distance timber transport. The fuel consumption for all operations necessary to produce 1 m³ of wood was 6.96 L/m³, and fuel consumption for timber truck transport was 2.33 L/m³ or 33.4% of the total fuel consumed (Anić et al., 1996). Karjalainen and Asikainen (1996) reported that fuel consumption in Finland was .56 L/km, while emissions of GHGs (CO₂, CH₄ and N₂O) were .03 kg/m³/km. According to Svenson (2011), fuel consumption in Sweden was .28 L/km, and according to Klvač et al. (2013), fuel consumption in the Czech Republic amounts to 2.19 L/m³ and .674 L/km. Pandur et al. (2015) stated that the energy consumption in all the operations necessary to produce 1 m³ of wood in Croatian lowland forests is 634 MJ/m³, of which fuel amounts to 86%. Of all operations necessary to produce 1 m³ of wood, the energy consumption of forest trucks during timber transport amounts to 31% of the total energy consumption. Šušnjar et al. (2019) stated an average fuel consumption of .543 L/km, which is less than the previous research results. They emphasize that newer forest trucks significantly contribute to reduced average fuel consumption.

Gross vehicle weight and payloads have a direct impact on fuel consumption. To reduce fuel consumption and GHG emissions for truck transport requires larger and heavier vehicles with big-ger payloads (Väätäinen et al., 2021).

One of the research goals was to determine the environmental suitability of timber truck transportation by measuring fuel consumption of forest trucks, and by comparing the measured fuel consumption with the longitudinal slope on forest roads. Furthermore, the objective was to define guidelines that would provide information to planners in the planning and design stage of constructing forest roads to reduce harmful exhaust emissions.

Methods

Research Area

The research was conducted in three separate areas within three different Forest Administrations (FA). Of the recorded data, only data from FA Gospić were used for the preparation of this article, while data from the remaining two, FA Bjelovar (Forest Office Grđevac) and FA Senj (Forest Office Novi Vinodolski), were insufficient for use in statistical analysis, due to the longitudinal configuration of the recorded forest roads. This issue is described in detail in the Materials and Methods section and in the Discussion section.

The research for the data used in this article was carried out at the Bakovac Kosinjski, Perušić locality (Figure 1), in the area from N 44°42'15", E 15°04'15" to N 44°44'30", E 15°11'38" (in the WGS84 geographic system), FA Gospić, a mountainous part of Croatia at an altitude of 500-1000 m. The forest roads on which the research was carried out are in indented terrain with large differences in levels between starting and ending points (Figure 2), and a high proportion of rock in the soil structure. Due to such terrain characteristics, forest roads are separated from public roads (with asphalt pavement) in the valley, and are directed to the highest areas of management units. On the forest roads studied in this research, sections of longitudinal slope from 3% to 9% prevail, while the total length of the forest road was measured as 16 952.57 m (Figure 1). The pavement structure of the researched roads consisted of 30–60 mm rock structure in the lower road layer and 0–30 mm in the upper road layer.

Data Acquisition

The purpose of this research is the application of remote monitoring of the forest trucks with the help of FMS and controller area network (CAN)-bus adapter, in order to gain insight into fuel consumption of an unloaded and an optimally loaded forest truck in relation to the longitudinal slope of forest roads,



Researched Forest Roads at the Locality Bakovac Kosinjski, Perušić.



while driving uphill and downhill. The FMS Plus CAN-bus device of brand Mobilisis WiGo were installed in the Forest Truck Assemblies (FTA), and following data were collected:

• GPS coordinates of the vehicle,

total fuel consumption. The forest truck consisted of a MAN TGS 33.440 truck, a hydraulic crane Epsilon Palfinger M110Z and a trailer PSM 200 (Figure 3). The total mass of the unloaded forest

truck amounted to 17 840 kg, and the allowed gross vehicle mass was 40 000 kg. This unit was driven only by a single driver, so there was no possibility of a measurement error caused by drivers' bias or their differing driving manners.

The installed Mobilisis WiGo system (FMS CAN-bus adapter) (Figure 4) was connected via CAN-bus to a computer in the forest truck used for the study, and the data on total fuel consumption



Figure 3.

Forest Truck MAN TGS 33.440 With Hydraulic Crane Epsilon Palfinger M110Z and Trailer PSM 200.



were transmitted over the GSM cellular network to a central server at Mobilisis. The data was accessed via a user interface and a personal computer, where it was stored afterward as .xlsx and .csv file types. The accuracy of fuel consumption measured with this system was .5 L. Along with fuel consumption, the Mobilisis WiGo system recorded current spatial position (i.e., x, y, and z coordinates) of the vehicle. The fuel consumption and vehicle coordinates were in .xlsx or .csv file types, and in relation to the time function. The frequency of recording the cumulative fuel consumption was 10 seconds, and the current position was recorded every 5 seconds.

In data collection, a linear–spatial method was used that included the use of two modern working instruments: a dual-frequency GNSS GPS receiver Magellan ProMark 500 and a Sokkia Total Station Series 3030R. To obtain the absolute coordinates and accurate positioning, the GNSS GPS receiver Magellan ProMark 500 was used, along with two reference points that later served as a link for the Total Station, which were recorded. The measured data were recorded in projection by the World Geodetic System (WGS 84) to be identically projected to data obtained from the FMS device. Using the recorded x, y, and z coordinates of the vertical grade level breaks of forest roads (middle of convex or concave curves) the longitudinal slopes of

road sections were obtained. The WGS 84 uses the GRS 80 reference ellipsoid.

Furthermore, in horizontal curves with radius smaller than 100 m, regardless of the longitudinal slope, the coordinates of points that represented a beginning, a middle, and an end of a particular horizontal curve were recorded.

For road sections between each .5 L change in fuel consumption, different slope classes were derived, which were slope class I (from 0% to 3%), slope class II (from 3.01% to 6%), and slope class III (from 6.01% to 9%). For each forest road section within one slope class, the average longitudinal slope and fuel consumption expressed in liters per kilometer were calculated.

When driving a loaded and an unloaded forest truck, fuel consumption was expressed as a function of the driven length, as liters per kilometer. Carbon dioxide emissions were expressed in kilograms per ton per kilometer, where CO_2 emissions were calculated using conversion values taken from the manual DEFRA (2012) which states that the combustion of 1 L of diesel fuel creates 2.6569 kg of CO_2 .

As noted in the Research Area section, the study was conducted in three FAs and data from two FAs were not used for analysis. The reason for this lies in the fact that with the minimum change of consumption as .5 L. for forest roads with a highly variable longitudinal slope (+; -), the determination of the average consumption of fuel, within .5 L according to slope categories was impossible whether trucks were driven loaded or unloaded when the consumption exceeded a certain section with uphill and downhill transportation. Such data were excluded from further analysis, and only data where a fuel consumption reduction of .5 L was achieved within a particular slope category when driving uphill or downhill were used.

Spatial and Statistical Analysis

For data analysis and database collection, MS Excel 2013 was used. For spatial data analysis, the computer software ESRI ArcGIS 10.4.1 package was used, while the statistical analysis was conducted with the StatSoft Statistica 8 software package.

The flowchart and processing data graphically clarify the sequence of work from data collection, database creation, data unification, and toward the final formation of results after deciding which data to take into analysis and which to discard (Figure 5).

Results

The precision of measurement of fuel consumption with a builtin measuring system was .5 L. In this manner, measurements under favorable conditions of transport (driving unloaded forest truck plus slight road slope plus driving downhill) by forest truck amount to a relatively large distance with .5 L of fuel. Since the goal of this research was to show the dependence of forest truck's fuel consumption on the longitudinal slope of the road, while the study area consisted of relatively short sections of Pandur et al. Energy Efficiency of Timber Transport by Trucks Forestist 2021: XX(XX): 1-10



Diagram of the Data Flow of the Whole Process Until the Final Decision Making and Obtaining the Results.

forest roads having a constant longitudinal slope, it was impossible to collect sufficient data on fuel consumption when the unloaded forest truck was driven downhill. For this reason, data on fuel consumption depending on the longitudinal road slope while driving downhill were not sufficient for quality analysis.

The diagram in Figure 6 shows the dependence of fuel consumption on forest road sections with average longitudinal slope while driving an unloaded forest truck. The diagram shows that the increase in slope increases fuel consumption exponentially, and ranges from .7 L/km at an inclination of 3.5%, to 1.6 L/km at an inclination of 9.5%.

The slope-dependence of the fuel consumption of a loaded forest truck driving on the section of the forest road with average longitudinal slope is shown in Figure 7. Fuel consumption

tends to increase exponentially with increase in slope, and ranges from 1.21 L/km with 0% slope to 3 L/km with of 8% slope. From these two figures, it can be concluded that a nominally loaded forest truck consumes on average 2.5 times more fuel in same longitudinal slope in relation to an unloaded vehicle.

While driving downhill, the driver has the ability to brake in three different ways. One method is by pressing and holding the brake pedal, which is not recommended because it shortens the durability of the brakes, and is not normally used for braking downhill. Another method is by means of braking with the engine of the forest truck, which also is not used while driving down the high slopes because engine overload may occur. The third method, which is the most used method of braking, is braking with the help of a retarder. In many cases, depending on



Figure 6.

Fuel Consumption of Unloaded Forest Truck While Driving Uphill.



Fuel Consumption of Loaded Forest Truck While Driving Uphill.

the driving situation, these three methods of braking and their combinations are used.

The diagram in Figure 8 shows the dependence of fuel consumption on the longitudinal slope of sections of forest road while driving a loaded forest truck downhill. This dependence is explained by an exponential curve, and fuel consumption ranges from .87 L/km on a 3.2% slope to .1 L/km on a 7% slope. Higher fuel consumption when driving downhill on smaller slopes is due to the fact that the driver in such cases used the engine for braking and therefore consumed more fuel, and while driving down higher slopes he used the retarder for braking whose usage does not affect fuel consumption, because fuel consumption during braking with retarder is minimal regardless of whether the vehicle is loaded or unloaded.

In the same diagram, the data of fuel consumption dependency on the longitudinal slopes of forest road sections of Class I (0–3%) are not visible because the proportion of such road sections was relatively small and there were no changes while fuel consumption of .5 L was recorded.

The carbon dioxide emissions of a nominally loaded forest truck, depending on the class of the longitudinal slope of forest roads, is shown in Figure 9. The diagram shows that CO_2 emissions increase with longitudinal slope while driving a loaded forest truck uphill, while in the case of driving loaded forest truck downhill; with increase of longitudinal slope, CO_2 emissions decrease significantly.

Discussion, and Conclusion and Recommendations

The results obtained by measuring fuel consumption and data transfer as shown in this study are satisfactory. Data for the dependence of fuel consumption of loaded and unloaded forest truck fuel while driving uphill and driving loaded downhill



were also obtained. The problem lay in obtaining the data while driving an unloaded forest truck downhill, because the forest roads chosen for this research did not have long enough sections of the same class of longitudinal slope for the change in fuel consumption of .5 L. Future research should consider more frequent interval readings of fuel consumption, up to .1 L. Also, due to the appearance of slope changes both upward and downward in some sections of the road, together with the occurrence of more than one class of longitudinal slope within the minimum unit of fuel consumption, a significant number of road sections could not be considered. It is recommended that in future, a large number of forest roads with different longitudinal slopes are recorded, so that many more sections of road can be used. In addition, forest road sections used for analysis should have a constant longitudinal slope, to obtain a larger volume of comparable data. That was shown as an example in the FA Gospić area that was studied, where there were longer segments of forest roads with constant longitudinal slope, which can be seen in Figure 2.

From the available references, only Kure (1990, 1992) measured fuel consumption with respect to the category and the slope of



Figure 9. CO₂Emissions of Loaded Forest Truck Depending on Different Slope Classes While Driving Uphill.

forest roads. The author stated that the average fuel consumption amounted to 1.21 L/km while driving uphill, and .23 L/km while driving downhill. The results of our research show that an increase in slope increases the fuel consumption exponentially, which ranges from .7 L/km at an inclination of 3.5% to 1.6 L/km at an inclination of 9.5%. When driving downhill, fuel consumption ranges from .87 L/km at a 3.2% slope to .1 L/km at a 7% slope.

Kure (1990, 1992) also stated that fuel consumption while driving a loaded forest truck uphill with the increased number of RPM (higher than the optimum amount), depending on speed ranged from 1.01 L/km to 2.61 L/km. Our results show that fuel consumption tends to increase exponentially with increase of slope and ranges from 1.21 L/km with 0% slope to 3 L/km with of 8% slope.

In case timber is transported mainly uphill, forest roads should be designed with mild longitudinal slopes, because, as can be seen in Figure 7, with increasing slope class, emissions of GHGs will increase by up to 50% compared to the lower slope classes. Đuka et al. (2017) stated that increasing slope to about 50% doubles energy consumption and GHG emissions, while a slope of 70% almost triples them. In Croatia, the proposed design and construction of forest roads allows up to 8% of the longitudinal slope of the main forest road in the mountainous areas (Šikić et al., 1989), while for example in neighboring Italy (Laschi et al., 2016), construction of forest roads intended for traffic of forest trucks is even put to a maximum of 10% of maximum average longitudinal slope.

This research has not focused on the impact of horizontal curves and changes in their radius on fuel consumption or CO_2 emissions, which in future studies should certainly be investigated. The longitudinal slope of forest roads has a significant influence on fuel consumption by a forest truck. From the results obtained, it also can be concluded that the fuel consumption is significantly influenced by the driver as well, and the technique of slowing down the vehicle (braking), which can best be seen in the diagram shown in Figure 6, which shows the dependence of fuel consumption on longitudinal slope while driving loaded forest trucks downhill. A nominally loaded forest truck consumes on average 2.5 times more fuel on the same longitudinal slope compared to an unloaded vehicle. Concerning CO_2 emission, on slope class II (3.01–6%), CO_2 emissions are almost 3.5 times lower during driving downhill, and on the slope class II (6.01–9%), CO_2 emissions are even 24 times smaller.

In hilly and mountainous areas, forest trucks mainly transport timber from higher altitudes towards lower ones, that is, from the forest to the valley below, where the timber processing industries are mostly located. According to the results obtained as well as the environmental suitability of timber transport by forest trucks, this is a much more favorable scenario.

Future research should consider more frequent readings of fuel consumption at shorter intervals, measuring with every .1 L of consumption. In this case, interval readings of fuel consumption of every .5 L were not sufficient to obtain information for every situation of truck driving.

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