THE INFLUENCE OF ROAD CHARACTERISTICS

ON

FUEL CONSUMPTION FOR LOGGING TRUCKS

M Sc in Forestry at SLU - Swedish University of Agricultural Sciences. Researcher within forest transportation and forest roads.

G. SVENSON
Skogforsk, The Forestry Research Institute of Sweden

PhD Forest Operations
Assoc. professor Forest Logistics

D. FJELD
SLU - Swedish University of Agricultural Sciences

Abstract

Fuel costs account for more than 35% of the transport cost in Swedish forestry. In order to lower these costs it is important to understand the impact on fuel consumption of a number of factors. In this study the impact of gradient, curvature and road surface roughness has been studied, as well as their correlation to functional road class.

The study was done with a 60 ton logging truck in an area which captured high variation in the studied variables. Topography and road surface roughness was measured with a profilograph.

The results showed a high correlation between fuel consumption and gradient, curvature, road surface roughness and functional road class. Functional road class was also found to be correlated to both curvature and road surface roughness.

A function describing the impact of gradient and road surface roughness on fuel consumption was established and it shows that 77% of the variation in fuel consumption could be explained by these two variables.

Keywords: Logging truck, fuel consumption, gradient, curvature, road surface roughness, functional road class

1. Introduction

Transport accounts for more than 25% of the Swedish forest industries' roundwood procurement cost (exclusive stumpage) at mill gate. The cost has increased more than Consumers Price Index (CPI) over the last years, mainly explained by rapidly increasing fuel costs (Brunberg 2011). At present, fuel costs account for more than 35% of the transport cost in Swedish forestry.

In order to find ways of lowering roundwood transport costs it is important to understand the impact on fuel consumption by a number of factors, e.g. truck configuration, infrastructure standards, topography and even operator behaviour. A literature review reveals a wide selection of studies in many parts of the world, both within general transportation and within forestry.

1.1 General Studies on Fuel Consumption

When it comes to the interaction between the vehicle and infrastructure many studies have shown how road surfacing impacts rolling resistance and fuel consumption. The studies have been done by direct measurements of vehicle fuel consumption as well as coast-down studies. Other factors which have been studied include tyre pressure, axle distribution and vehicle weight (Segel 1982; Sävenhed 1987; du Plessis 1989; Sandberg 1990; Taylor 2002; Jonsson 2009; Sumitsawan 2009; Lenngren 2010; Surcel 2010).

Although road surfacing is an important factor for fuel consumption, there are a number of other factors that have a stronger influence on the overall fuel consumption for truck transport. These include grade, speed and the driver (Zaniewski 1979; Laurell 1985; Ecotraffic 1999).

One common objective of many studies has been the development of fuel consumption models. Areas of applications for these models include the development of decision support systems designed for improving vehicle routing and fuel economy (Hellström 2007; Hunt 2009; Huang 2010).

1.2 Fuel Consumption Studies for Logging Trucks

A number of studies have been conducted on fuel consumption for logging trucks, mainly in major forestry countries. Also here a number of factors have shown to have an impact on fuel consumption. Grade has the greatest impact, especially when fully laden (Peiyu 1987). Road surfacing has also been shown to be an important factor. When leaving paved roads, fuel consumption rises substantially (Peiyu 1987; McCormack 1990). Also tyre type and axle distribution have impacts (Ljubic 1989; Taylor 1990). Poor driving technique has been shown to increase fuel consumption by up to 11% (Nader 1991).

A few studies have also been done of logging trucks in Sweden. Under these conditions an average fuel consumption for a typical logging truck is 58 l/100 km (Brunberg 2009) and the variation around this average is substantial. Fuel consumption can vary + - 15% between drivers and the difference between the best paved roads and typical forestry roads increases fuel consumption up to 75% (Forsberg 2002; Forsberg 2002).

The route for a typical logging truck route under Swedish conditions is dominated by rural, low congestion areas and a variety of road standards, table 1 (Forsberg 2002).

Table 1 - The distribution of road standards for a typical logging truck route in Sweden (after Forsberg 2002).

Road standard	Proportion, %
High standard paved road	46
Low standard paved road	37
High standard gravel road	7
Low standard gravel road	10

The individual characteristics of roads are indirectly described by a number of classifications indicating both speed (geometry) and strength (bearing capacity). These classifications are described in the Swedish national road classification system, NVDB (Swedish Road Administration 2008).

The insight given by earlier studies on logging truck fuel consumption under typical Swedish road conditions is limited. In order to find ways of lowering fuel consumption for logging truck transport, there is a need for higher resolution studies quantifying the effect of the transport environment, specifically road characteristics related to topography and surface.

1.3 Objectives

The objective of this study was to quantify the influence of road characteristics on fuel consumption for a self-loading 60 ton logging truck. The study examines the impact of gradient, surface roughness and curvature. The study also couples the results to the Swedish national road classification system, NVDB.

2 Material and Methods

2.1 Study Area and Conditions

In order to capture sufficient variation in the independent variables (gradient, curvature and road surface roughness) a 300 km long route was assembled in Värmland in the south-western part of Sweden.

The study of fuel consumption was conducted July 14, 2011. The temperature varied between 10 and 20° C. There was moderate wind and no precipitation. The date was chosen to represent dry conditions, and it was preceded by a long period of hot and dry weather.

2.2 Data Collection

The collection of data included two dependent variables – fuel consumption and vehicle speed and two independent variables - road surface roughness and topography.

Fuel Consumption and Vehicle Speed Measurement

The study of fuel consumption and vehicle speed used a conventional self-loading logging truck (table 2). The driver had 7 years of experience in operating logging trucks under these conditions.

Table 2 - Vehicle data

Truck and trailer	
Net vehicle weight	23 200 kg
Gross vehicle weight	60 000 kg
Gross vehicle length	22 m
No. bunks	10
Tyre brand	Continental
Truck	
Brand	Volvo
Model	FH
Model year	2008
Mileage	566 000 km
Weight	15 600 kg
Engine	13 litre, 520Hp
Gear box	Manual
Drivetrain	6X4
Tyre dimension and pressure	
• Steering (single)	385/65R22.5, 9 bar
• Drive (dual)	315/80R22.5, 7 bar
Crane	Removable
Trailer	
Model year	2005
Axles	4
Weight	7 600 kg
Tyre dimension and pressure (dual)	265/70R19.5, 9 bar

Fuel consumption and vehicle speed data was collected with equipment developed by VDI Innovation, (Drivec AB) which inductively reads and interprets the CAN-bus communication in the truck.

Road Surface Roughness and Topography Measurement

Road surface roughness and topography measurement was done by Vectura Profilograph P45. This equipment produced a profile of the road by combining length measurement with lasers and inertial sensors (Ahlin 2004). Different kinds of surface and road roughness variables are also produced by this equipment. In this study IRI (International Roughness Index) was chosen to describe road surface roughness. The measurements are shown in table 3.

Table 3 - Measurement methods for dependent and independent variables

	Measurement	Variable	Unit	Frequency	Position source
Dependent variables	Truck/CAN-bus	Fuel consumption	ml	10 Hz	GPS on truck
		Velocity	m/second		
Independent variables	Profilograph	Gradient	m/100 meter	1/meter	GPS on profilograph
		Curvature	1000/radius, meter		
		Surface roughness (IRI)	mm/meter		

2.3 Data Management and Statistical Analysis

The data from the two sources (Truck/CAN-bus and Profilograph) was merged meter by meter using the function Spatial Join in the GIS programme ArcMap10 (ESRI 2011). The 300 km route was cut into 500 m sections, giving approximately 600 observations. Statistical analysis of the data was done in the statistical programme R (R Development Core Team 2011). The resulting distribution of 500 meter sections according to the NVDB functional road classification system is shown in figure 1. The average values, min, max and standard deviation for individual road characteristics are shown in table 4.

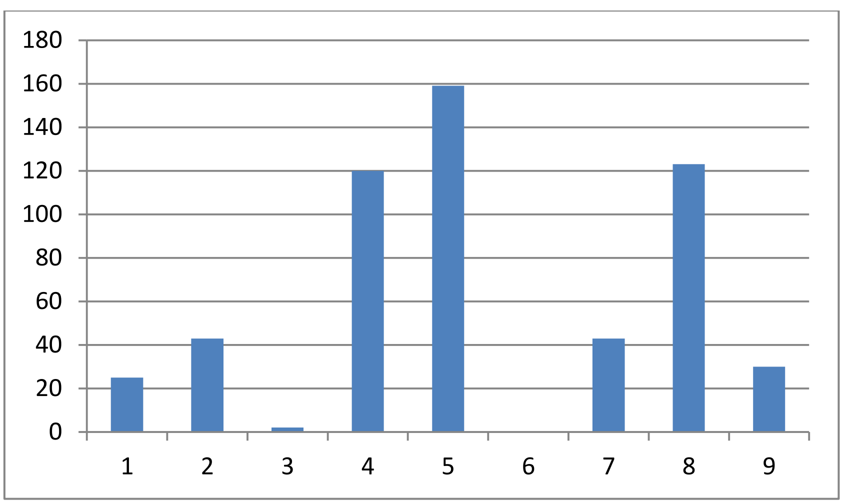

Figure 1 - Distribution of road sections per functional road class

Table 4 - Average values, min, max and standard deviation for gradient (%), curvature (1000/r) and surface roughness (IRI).

Variable	Average	Min - Max	Standard deviation
Gradient (%)	0.10	-8.59 – 8.66	2.07
Curvature (r)	2.90	0.00 – 12.71	2.41
Surface roughness (IRI)	3.93	0.83 – 18.90	2.49

3. Results

The results from the study showed, as expected, a high variation in both fuel consumption and velocity over the different 500 m long road sections, table 5.

Table 5 - Fuel consumption and velocity over the 500 meter road sections.

Variable	Average	Min - Max	Standard deviation
Fuel consumption, litres/100 km	85.0	0.00 – 469.6	61.6
Velocity, m/s	13.71	3.70 – 25.06	4.39

The Pearson correlation test showed that fuel consumption was correlated to gradient, curvature, road surface roughness, and functional road class, table 6. Gradient was the variable with the highest correlation to fuel consumption. Furthermore, functional road class was found to be correlated with both curvature and surface roughness. Because curvature and surface roughness, (IRI), were also highly correlated to each other, it was assumed that road class captures the effects of both.

Table 6 – Pearson correlation matrix of the dependent and the independent variables.

	Gradient	Curvature	IRI	Road class
Fuel consumption	0.77	0.26	0.37	0.27
Gradient	1	- 0.04	0.01	0.02
Curvature		1	0.49	0.38
IRI			1	0.67

Because of low number of observations for certain functional road classes they were aggregated into 5 more general classes with higher number of observations per class and a clear progression of average values, for both the dependent and independent variables, table 7.

Table 7 - The 9 functional road classes were aggregated into 5 general classes.

Road class	Fuel consumption, litres/100 km	Velocity, m/s	Gradient	Curvature	IRI, mm/m	No. of observations
1-4	66.95	18.14	0.25	1.25	1.92	190
5	75.87	13.24	-0.07	3.65	3.57	159
7	95.94	9.88	-0.03	2.93	6.34	43
8	102.07	11.12	0.12	3.19	5.46	123
9	145.19	8.23	0.36	5.06	7.50	30

Road class can accurately describe fuel consumption due to its correlation to IRI and curvature, but it misses the impact of the independent variable gradient. A regression of gradient against fuel showed a high coefficient of determination, and adding the continuous variable IRI, resulted in a function where 77 % of the variation can be explained by these two factors alone:

$$Fuel = 46.19 + 22.33*G + 1.47*G*G + 7.70*IRI \quad (1)$$

Looking at the effect of gradient alone, a clear dog-leg occurred between driving uphill and downhill. When going uphill fuel consumption increased more with increased gradient, than the corresponding decrease when going down-hill, figure 2.

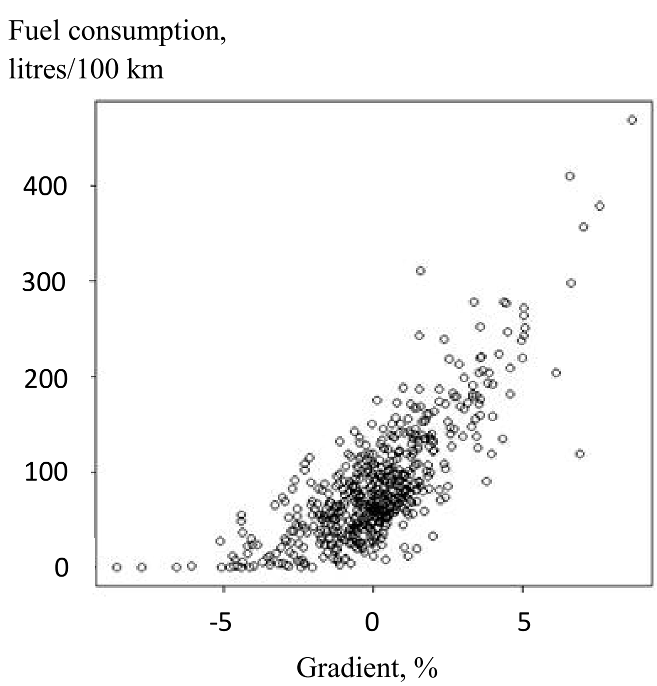

Figure 2 – A scatter plot of fuel consumption (litres/100 km) and gradient (%).

4. Discussion

The objective of this study was to quantify the influence of road characteristics on fuel consumption for a self-loading 60 ton logging truck. The results so far show that 77% of the variation in fuel consumption could be explained by two of the registered variables; gradient and road surface roughness (IRI).

The preliminary analysis of the independent variables showed strong correlations between curvature, surface roughness and functional road class. This indicated that functional road class captures variation in a number of specific road characteristics. For this reason functional road class is a practically useful variable for predicting fuel consumption. The results from this study follow the effects indicated earlier by Forsberg (2002) and also follow the consumption trends modeled by a practical cost calculation model (Gillecalc 2010). Functional road class is, however, a subjective measure, aiming at describing the roads function in a road network and does not directly describe the topography or surface of the transport environment. Tighter curves and rougher road surfaces are typical for lower-class roads in general. In other areas of Sweden, functional road class will have another distribution of gradients and curvature and the general influence of road class may therefore vary. This requires that future studies should build on a broader sample of road networks. The proposed model applies only to the studies combination of truck and driver. A more general model requires a broader sample of trucks and operators.

Given the experiences of this study, there is still a need to model fuel consumption with a higher resolution of specific road characteristics. The methods used to quantify the independent variables are sufficient for the degree of precision required. There may be, however, simpler ways of measuring topography and road surface. Road roughness could be measured with the use of truck-mounted accelerometers. Horizontal and vertical road curvature could perhaps be estimated with a high precision GPS. The impact of topography, however, is only partially captured by gradient per 500 m stretch. It would therefore be of interest to quantify the undulation of topography (hilliness or “roller coaster effect”).

The results reported in this paper represent only a portion of a larger complete study examining the impact of load weight and seasonal variation in road conditions on fuel consumption. Analysis of the whole data set will involve a high resolution modeling of the effect of individual road characteristics on both fuel consumption and travelling speed. This knowledge will make it possible to more accurately model transport costs under varying transport environments. This may enable better routing of round wood transport and the development of transport tariffs which better reflect regional conditions.

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