THE IMPACT OF ROAD GEOMETRY AND SURFACE ROUGHNESS ON FUEL CONSUMPTION FOR SWEDISH LOGGING TRUCKS

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Abstract

In Sweden, diesel accounts for more than one third of the secondary haulage cost. Many factors influence fuel consumption such as vehicle weight, velocity, road surface, driver, truck configuration and curvature, factors poorly quantified under Swedish conditions.

The goal of this study was to quantify the impact of road geometry, road surface roughness and vehicle weight on fuel consumption for logging trucks. This study is a further development on a study presented at HVTT12 conference in Stockholm 2012. The study was conducted in the western part of south Sweden under dry summer and wet autumn conditions. The study included 1800 km of high resolution data collection over both public and forest roads.

The average fuel consumption during the study was 71.4 litres/100 km. On the best public roads fuel consumption was 62.6 litres/100 km and on the forest roads 129.8 litres/100 km. The results also indicate differences in fuel consumption between the summer and autumn studies on both public and forest roads. The analysis showed strong correlations between the independent variables gradient, curvature, surface roughness and functional road class.

Keywords: Logging Truck, Fuel Consumption, Gradient, Curvature, Road Surface Roughness, Integrated Gradient, Functional Road Class, Vehicle Weight.

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, 2012). 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, geometry and even operator behaviour. In a previous paper presented at HVTT12 conference in Stockholm 2012 the impact of topography and surface roughness for a 60 ton logging truck under dry summer conditions was examined.

1.1 Objectives

The goal of this study was to quantify the impact of gradient, curvature, road surface roughness and vehicle weight on fuel consumption for a logging truck. The study investigates a conventional self-loading timber truck with gross vehicle weight (GVW) of 60 tons.

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 tests track on both public and forest road was assembled in the county Värmland in the south-western part of Sweden.

The studies of fuel consumption and vehicle speed were conducted under stable weather conditions, the wet autumn study in November 2010 and the dry summer study in July, 2011. There was moderate wind and the temperature varied between 10 and 20° C in July and was 5° C in November. The dates were chosen to represent wet and dry conditions, and was preceded by a long periods of stable weather. Each study was initiated with an empty truck (ca. 23 tons), followed by half loaded (ca. 43 tons) and finally with fully loaded truck (ca. 60 tons).

2.2 Data Collection

The collection of data included two dependent variables – fuel consumption and vehicle speed and three independent variables – gradient, curvature and surface roughness.

Fuel Consumption and Vehicle Speed Measurement

The study of fuel consumption and vehicle speed used a conventional 22 m long, self-loading logging truck with a maximum GVW of 60 tons.

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 Geometry Measurement

Road surface roughness and geometry measurement was done by Vectura Profilograph P45. The measurements are shown in table 1.

Table 1 - Measurement methods for dependent and independent variables

	Measurement	Variable	Unit	Frequency	Position source
Dependent variables	Truck/CAN-bus	Fuel consumption Velocity	ml m/s	10 Hz	GPS on truck
Independent variables	Profilograph	Gradient Curvature Surface roughness	% m^{-1} mm/m	1/m	GPS on profilograph

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 1000 m sections, giving approximately 1700 observations. Statistical analysis of the data was done in the statistical programme R (R Development Core Team, 2011). The resulting distribution of 1000 meter sections according to the NVDB functional road classification system (Swedish Road Administration, 2008) is shown in figure 1. The average values, min, max and standard deviation for individual road characteristics are shown in table 2.

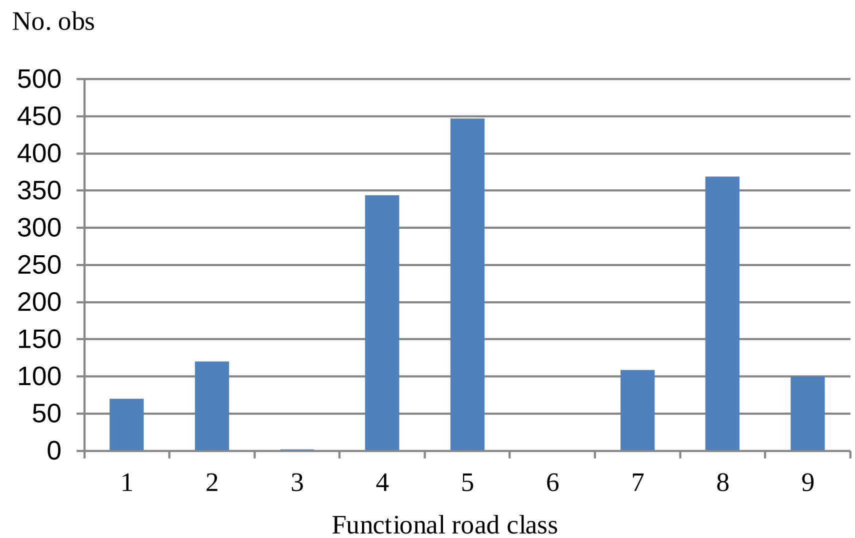

Figure 1 - Distribution of road sections (1000 m) per functional road class.

Table 2 - Average values, range and standard deviation for gradient (%), curvature (1000/r) and surface roughness (mm/m).

Variable	Average	Min - Max	Standard deviation
Gradient (%)	0.09	-7.79 – 7.85	1.75
Curvature (1000/r)	2.93	0.00 – 11.67	2.06
Surface roughness (mm/m)	3.98	0.89 – 17.31	2.36

3. Results

The average fuel consumption the whole study was 71.4 litres/100 km. Fuel consumption varied with GVW (Table 3).

Table 3 - Average fuel consumption (litres/100 km) for different gross vehicle weights (tons) during the study.

GVW (t)	*Fc* (litres/100 km)
23	48.8
43	74.5
60	90.8
All weights	71.4

The seasonal variation in fuel consumption is shown in figure 2. The greatest variation is seen for road classes 8 and 9.

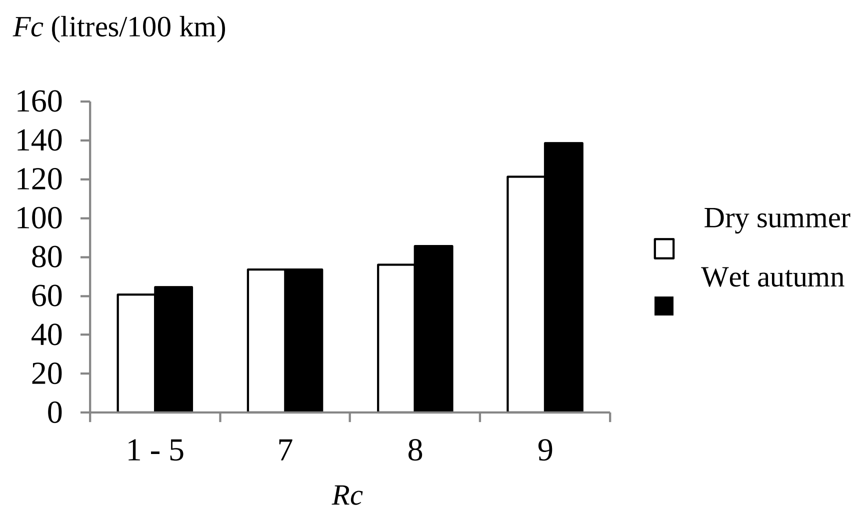

Figure 2 – Average fuel consumption (litres/100 km) per functional road class (Rc) for the dry summer and wet autumn replication.

A Pearson correlation test showed that fuel consumption was correlated to gradient, curvature, road surface roughness and functional road class, table 4.

Table 4 – Pearson correlation matrix of the dependent and the independent variables.

	Gradient	Curvature	Surface roughness	Road class
Fuel consumption	0,68	0,27	0,38	0,27
Gradient		-0,03	0	-0,02
Curvature			0,52	0,40
Surface roughness				0,69

Because of the low number of observations for certain functional road classes they were aggregated into 4 more general classes with higher number of observations per class, giving a clear progression of average values for both the dependent and independent variables, table 5. Here it can be noticed that leaving the better road classes (1-5) for forest roads (7-9) increases fuel consumption with up to 100%. This is mainly due to increased curvature and road surface roughness, figure 3.

Table 5 – Average values of dependent and independent variables for the 4 aggregated road classes.

Road class	Fuel consumption, litres/100 km	Velocity, m/s	Gradient, %	Curvature, m^{-1}	IRI, mm/m	No. of observations
1-5	62.6	16.4	0.1	2.6	2.8	1116
7	73.6	11.3	- 0.2	2.8	6.4	109
8	80.7	12.3	0.1	3.0	5.2	369
9	129.8	8.8	0.4	4.9	7.5	100

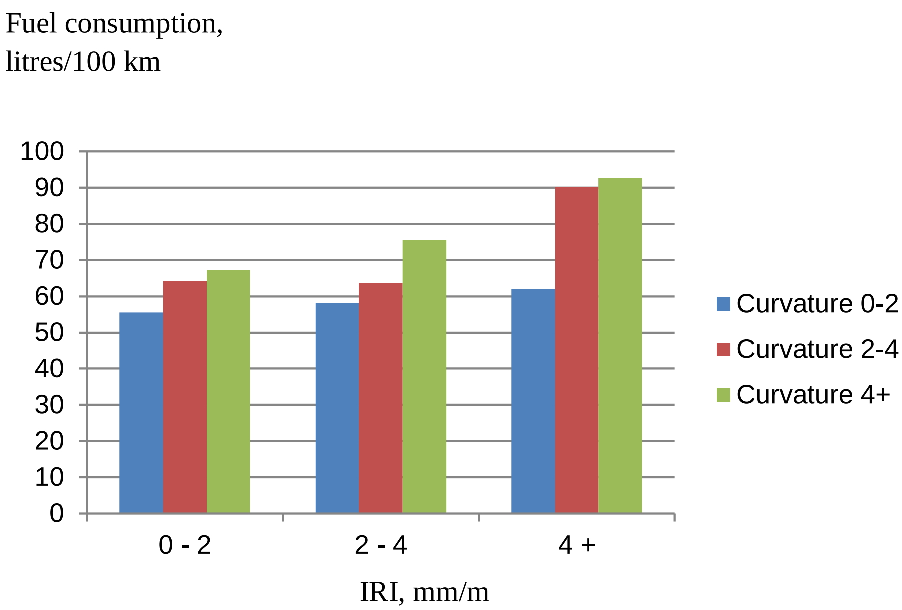

Figure 3 – Average fuel consumption (litres/100 km) for different classes of road surface roughness (mm/m) and curvature (1000/r).

Road class clearly influences fuel consumption due to its inherent correlation with surface roughness and curvature. Its effect through the associated variation in gradient, however, is not as straightforward. Examining the effect of gradient alone, there is a clear difference in the slope between uphill and downhill driving, figure 4. When driving uphill fuel consumption increased more with increasing gradient, than the corresponding decrease when driving down-hill.

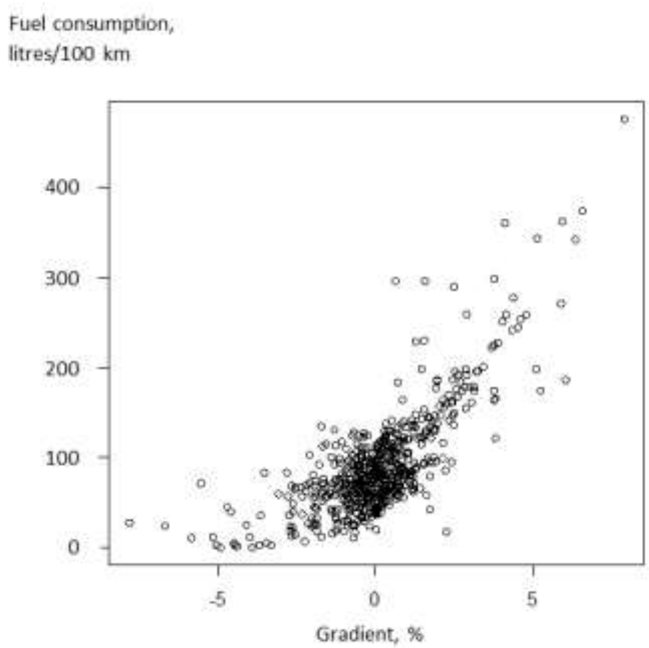

Figure 4 – A scatter plot of fuel consumption (litres/100 km) and road gradient (%).

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 average fuel consumption was 71.4 litres/100 km. The difference between the best public roads and the forest roads was substantial, 62.6 litres/100 km and 129.8 litres/100 km respectively. The higher fuel consumption on the forest roads can be explained by greater curvature and a rougher road surface. The results also indicate differences in fuel consumption between the summer and autumn studies on both public and forest roads. This variation in fuel consumption can be explained by the difference in gravel moisture content, but also other factors may play a role such as temperature or speed.

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. The results from this study follow the effects indicated earlier by Forsberg (Forsberg et al., 2002) and also follow the consumption trends modelled by a practical cost calculation models. Functional road class is, however, a subjective measure, aiming at describing the roads function in a road network and does not directly describe the geometry 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 impact of gradient on fuel consumption is only partially captured by gradient (%) per 1000 m stretch. Grade (%) describes the average inclination between the starting and ending point of a road section and it would therefore be of interest also to quantify the effect of variation in gradient (integrated gradient) over longer distances. Integrated gradient would measure the additional vertical gain not already described by grade

Fuel accounts for approximately one third of the transport cost in Swedish forestry, wages another one third. If the impact of road geometry and surface roughness on travelling speed also could be modelled, it would obtain a good basis to more accurately model transport costs under varying transport environments and even improve road investment and maintenance calculations. This knowledge may also enable better routing of roundwood transport and the development of transport tariffs which better reflect regional conditions.

5. References

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