THE IMPACT OF ROAD GEOMETRY AND SURFACE ROUGHNESS ON DRIVING SPEED FOR SWEDISH LOGGING TRUCKS

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Abstract

Transport accounts for more than 25% of the Swedish forest industries’ roundwood procurement cost at mill gate (exclusive stumpage). Wages accounted for 34.2% of truck transport costs, so in order to further reduce transport costs and increase productivity it is important to better understand the impact of the transport environment on truck speed. This study quantified the impact of curvature, road surface roughness, gradient, integrated gradient and truck weight on driving speed. The study was done with a conventional 60 ton logging truck in an area which captured high variation in the studied variables.

The results quantified the correlation between driving speed and the independent variables curvature, road surface roughness and functional road class. Functional road class was also found to partially capture variation in curvature, integrated gradient and road surface roughness. Further analysis of the data will focus on developing a complete empirical model for improving forestry transport planning and costing of logging truck transport as well as the further refinement of the route selection system Calibrated Route Finder.

Keywords: Speed, Logging Truck, Curvature, Surface Roughness, Gradient, Integrated Gradient, Vehicle Weight, Gravel Road, Functional Road Class
1. Introduction

Transport accounts for more than 25% of the Swedish forest industries’ roundwood procurement cost (exclusive stumpage) at mill gate, where wages alone accounted for 34.2% of these (Brunberg 2012; Statistics Sweden 2014). The current trend of increasing transport costs are expected to continue in the future, motivating further R&D investments to increasing efficiency.

A wide range of studies has been done on heavy vehicle driving speeds, mainly within general transportation but also within forestry. In North America earlier studies of logging truck driving speeds have been carried out to predict travel time for cost modeling, design optimization or to determine the most efficient haul routes. The Logging Road Handbook, also known as BNG, was developed to support road and logging engineers when calculating the effect of road geometry and surface on logging costs (Byrne et al. 1960). A travel time prediction model has also been developed to improve transport planning in biomass operations (Simwanda 2010). In this case the estimation is done in a two-step simulation methodology where the first step calculates the maximum speeds per road segment and the second step simulates the driver’s behavior and calculates the travel time. In Sweden, an empirical study was conducted by Bohm et al. during the 1960’s on the impact of road standard on heavy vehicle speed (Bohm et al. 1964). Variables that were taken into account include load combination and weight (truck and trailer), road standard (gradient, curvature and surface) and sight distance. Given the gradual development of road standards and truck configurations, what is lacking now is a comprehensive, easy to use model which enables further development of transport planning in the Swedish forestry sector.

The objective of this study was to explore the influence of road geometry, surface roughness and vehicle weight on the driving speed of a conventional Swedish self-loading logging truck as well as, in the next phase of the work, to propose a complete empirical driving speed model.

2. Material and Methods

A 320 km long test track on both public and forest road was assembled in Värmeland county in south-western Sweden. The studies of vehicle speed were conducted for wet autumn conditions during November 2010 and for dry summer conditions during July, 2011. Each study was started with an empty truck (ca. 23 tons), followed by half loaded (ca. 43 tons) and finally with fully loaded truck (ca. 60 tons).

The collection of data included one dependent variable – vehicle speed and four independent variables – curvature, surface roughness, gradient and integrated gradient. Integrated gradient, in contrast to average gradient, describes the total vertical work done by the truck over a distance in an undulating topography, figure 1. The study used a conventional 22 m long, self-loading logging truck with a maximum GVW of 60 tons. 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. Measurement of road surface roughness and geometry was done with a Vectura P45 Profilograph; a high speed profilometer, equipped with lasers, inertial sensors and GPS, figure 2 (Ahlin et al. 2004). Each segment was also classified in terms of functional road class, where classes 1-6 and 7-9 are most often public roads and private forest roads respectively (Swedish Road Administration 2008).
The impact of road geometry and surface roughness on driving speed for Swedish logging trucks

Figure 1 – Graphical presentation of how the variables gradient (Gr) and integrated gradient (Ig) were measured and how the total data set was cut into road sections of different lengths.

The data from the two sources (Truck/CAN-bus and Profilograph) was merged metre-by-metre using the Spatial Join function in ArcMap10 (ESRI 2011). The 320 km route was cut into road sections of different lengths, but 1000-metre road sections were used in the following analysis, giving approximately 1700 observations. The analysis was done in the statistical programme R (R Development Core Team 2011).

Figure 2 – The Vectura P45 Profilograph was used for the accurate measurement of road geometry and surface roughness.
3. Results

The average speed for the whole study was 14.6 m/s. The average speed decreased by 13% between the empty and fully loaded truck. Average driving speeds were higher during the study under dry summer conditions. The difference between dry summer and wet autumn conditions was 6% and 8% for GVWs of 23 tons and 43 tons, respectively (Figure 3). In the following analysis the whole material was used without distinction between dry and wet conditions.

![Figure 3 – Average speed (Sp) for different truck weights (Wt) and during the dry summer and wet autumn study periods.](image)

The average speed was 86% higher on road classes 1-5 (public roads) compared to road class 9 (private forest roads). The highest values for curvature and surface roughness were registered on the private roads, particularly forest truck roads (Rc 8–9). Values for gradient and integrated gradient did not exhibit any clear trend with respect to road class (Table 1).

### Table 1 – Average values for speed (Sp), and the independent variables gradient (Gr), integrated gradient (Ig), curvature (Cu) and surface roughness (Rsr) by functional road class (Rc).

<table>
<thead>
<tr>
<th>Rc</th>
<th>Sp (m/s)</th>
<th>Gr (%)</th>
<th>Ig (%)</th>
<th>Cu (m⁻¹)</th>
<th>Rsr (mm/m)</th>
<th>No. obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>16.4</td>
<td>0.1</td>
<td>0.6</td>
<td>2.6</td>
<td>2.8</td>
<td>1116</td>
</tr>
<tr>
<td>7</td>
<td>11.3</td>
<td>-0.2</td>
<td>1.2</td>
<td>2.8</td>
<td>6.4</td>
<td>109</td>
</tr>
<tr>
<td>8</td>
<td>12.3</td>
<td>0.1</td>
<td>0.9</td>
<td>3.0</td>
<td>5.2</td>
<td>369</td>
</tr>
<tr>
<td>9</td>
<td>8.8</td>
<td>0.4</td>
<td>0.6</td>
<td>4.9</td>
<td>7.5</td>
<td>100</td>
</tr>
</tbody>
</table>

A Pearson correlation test was used to quantify the relationships between speed, curvature, surface roughness, functional road class, gradient and integrated gradient (Table 2). Speed was negatively correlated to curvature, surface roughness and functional road class. Speed also had a weaker negative correlation to gradient and integrated gradient. Functional road class was negatively correlated with truck speed, and positively correlated to integrated gradient, curvature and surface roughness.
The first component explained 52% of variance in the data and comprised of surface roughness (loading 0.48), road class (loading 0.46), curvature (loading 0.42) and integrated gradient (loading 0.46). The second component explained 17% of variance and comprised of gradient (loading -0.94) and integrated gradient (loading 0.31).

Given the multicollinearity identified in the correlation test, a principal components analysis (PCA) was carried out to further clarify these relationships (Figure 4). The first component explained 52% of variance in the data and comprised of surface roughness (loading 0.48), road class (loading 0.46), curvature (loading 0.42) and integrated gradient (loading -0.33). The second component explained 17% of variance and comprised of gradient (loading -0.94) and integrated gradient (loading 0.31).

Table 2 – Correlation matrix between driving speed, Sp, (m/s), gradient, Gr, (%), integrated gradient, Ig, (%), curvature, Cu, (m⁻¹), road surface roughness, Rsr, (mm/m) and road class (Rc) as quantified by the Pearson correlation coefficient (r).

<table>
<thead>
<tr>
<th></th>
<th>Sp</th>
<th>Gr</th>
<th>Ig</th>
<th>Cu</th>
<th>Rsr</th>
<th>Rc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp</td>
<td>1</td>
<td>-0.06*</td>
<td>-0.39***</td>
<td>-0.69***</td>
<td>-0.73***</td>
<td>-0.70***</td>
</tr>
<tr>
<td>Gr</td>
<td>1</td>
<td>1</td>
<td>-0.11***</td>
<td>-0.03</td>
<td>0</td>
<td>-0.02</td>
</tr>
<tr>
<td>Ig</td>
<td></td>
<td>1</td>
<td>0.34***</td>
<td>0.38***</td>
<td>0.38***</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td></td>
<td>1</td>
<td>0.52***</td>
<td>0.40***</td>
<td></td>
</tr>
<tr>
<td>Rsr</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0.69***</td>
<td></td>
</tr>
<tr>
<td>Rc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Examining the effect of integrated gradient (Ig) on speed (Sp) in figure 5, an increase in integrated gradient decreased speed on public roads, but not on private roads. Regarding the relation between speed and gradient (Gr), speed increased when going downhill on public roads, but decreased on private roads. Ascending grades decreased speed on both types of roads. Surface roughness led to a similar decrease of speed on both on public and private roads.

Figure 4 – Principal Components Analysis loading plot for the variables truck speed (Sp), gradient (Gr), integrated gradient (Ig), curvature (Cu), road surface roughness (Rsr) and road class (Rc).

HVT14: The impact of road geometry and surface roughness on driving speed for Swedish logging trucks
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Figure 5 – Boxplots of Speed (Sp) versus integrated gradient (Ig), gradient (Gr) and surface roughness (Rsr) by classes of functional road class (Rc) 1–5 (left) and 7–9 (right). The thick line is the median, and the lower and upper limitations of the box represent the first and third quintiles respectively.

Regarding the effect of curvature on speed, the effect was greater on private than public roads (Figure 6 left). Because of the correlation between curvature and surface roughness, figure 6 also shows the effect of curvature for two groups of surface roughness (IRI<=2 mm/m and IRI>=7 mm/m). Low road surface roughness values dominate on roads with low curvature and speed was correspondingly higher for these.
4. Discussion

The objective of this study was to explore the influence of road geometry, surface roughness and vehicle weight on the travelling speed of a conventional Swedish self-loading logging truck. The results showed how travelling speed for a Swedish logging truck varies with curvature, road surface roughness, gradient, integrated gradient and functional road class, road features which are generally correlated and have interacting effects on speed.

Under the conditions of this study curvature proved to be the primary determinant of speed. BNG attributes speed reductions in curves to the risk of slipping or roll-over on two lane roads, and sight distance on single lane roads (Byrne et al. 1960). The current study shows higher speeds on public roads than private roads of comparable curvatures. This can be an effect of increased sight distance for wider as public roads, but can also be the result of the correlated higher levels of surface roughness normally found on private roads. The limited sight distance and reduced width are the most probable explanation for the shown decrease in downhill speeds on forest roads. The driver operating the vehicle noted that running a 60-ton vehicle downhill on a single lane road requires considerable attention to both remain on the road and maintain a sufficient stopping distance for meeting other vehicles.

Further analysis of the data will focus on a complete empirical model describing the impact of curvature, surface roughness, gradient and integrated gradient on travelling speed, as well as their interactions. The final model will be useful for improved forestry transport planning and costing of logging truck transport and in the further refinement of the route selection system Calibrated Route Finder used by the forestry sector in Sweden.

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5. References

- Simwanda M. 2010. Modeling biomass transport on single lane forest roads and monitoring GPS accuracy for vehicle tracking under different forest canopy conditions.