Optimized Route Selection for Logging Trucks

Improvements to *Calibrated Route Finder*

Gunnar Svenson
Faculty of Forestry
Department of Forest Resource Management
Umeå

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Abstract

The forestry sector is playing an important role in the transition to a bio-economy. In the supply chain of forest raw material, logging transport is a crucial component. The forestry sector must improve transport efficiency to mitigate its impact on the environment, to reduce costs and road safety risks, and to remain competitive.

Forestry transport in Sweden is paid according to payload and distance travelled. The forestry sector has developed a system for distance measurement, Calibrated Route Finder (CRF), which balances quantitative factors, such as distance, functional road class and road width, with qualitative factors, such as stress and traffic safety. An inverse optimization process is used to translate best-practice routes into a weighted objective that is used when new routes are generated.

The objectives of this thesis have been to improve CRF, by including features describing road curvature and hilliness, and addressing illegal or impossible turns in intersections. Methods have been developed to calculate curvature and hilliness using available data in the national road data base. The study has proposed an augmentation of the road data network so that illegal, non-logical and undesirable turns and short-cuts can be considered. The augmented network also enables detailed descriptions of increased time and fuel consumption in relation to intersections, which provides opportunities to generate routing with a focus on minimizing cost or greenhouse emissions.

Two of the major cost elements in logging transport are time and fuel consumption, and this study has shown that fuel consumption is mainly affected by road gradient and truck weight, while operating speed is mainly affected by horizontal curvature and surface roughness. A new variable was introduced, integrated gradient, which describes the vertical work performed by the truck on undulating road sections better than the gradient variable.

Keywords: Distance measurement, fuel consumption, road characteristics, intersections, inverse optimization, remuneration system, speed modelling, surface roughness.

Author's address: Gunnar Svenson, Skogforsk, Uppsala Science Park,
SE-751 83 Uppsala, Sweden.

Dedication

To my family.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Gunnar Svenson* & Dag Fjeld (2016). The impact of road geometry and surface roughness on fuel consumption of logging trucks. *Scandinavian Journal of Forest Research,* 31(5), *pp*. 526–536.

II Gunnar Svenson* & Dag Fjeld (2016). The impact of road geometry, surface roughness and truck weight on operating speed of logging trucks. *Scandinavian Journal of Forest Research*. (Published online: 13 Dec 2016)

III Gunnar Svenson*, Patrik Flisberg & Mikael Rönnqvist (2016). Using Analytics in the Implementation of Vertical and Horizontal Curvature in Route Calculation. *IEEE Transactions on Intelligent Transportation Systems, 17(6), pp. 1772-1785.*

IV Gunnar Svenson*, Patrik Flisberg & Mikael Rönnqvist (2016). An augmented network for improved route generation using detailed description of turning in intersections. (Submitted manuscript)

V Gunnar Svenson*, Patrik Flisberg, Mikael Rönnqvist & Lars-Erik Jönsson (2016). Calibrated Route Finder – social, safe, environmental and cost-effective truck routing. (Submitted manuscript)

Papers I, II and III are reproduced with the permission of the publishers.

* Corresponding author

The contributions made by Gunnar Svenson in the papers included in the thesis are as follows:

I Formulated the original idea, conducted all literature review, all data collection and most of the writing of the manuscript. Worked with co-author on study design, data analysis and model construction.

II Formulated the original idea, conducted all literature review, all data collection and most of the writing of the manuscript. Worked with co-author on study design, data analysis and model construction.

III Helped formulate the original idea and assisted in design and implementation of the study. Worked with co-authors on data analysis and preparing the manuscript.

IV Worked with co-authors on formulating the original idea, study design, implementation of the study, data analysis and preparing the manuscript.

V Worked with co-authors on defining the scope of the study, formulating the content, supplied the information and preparing the manuscript.

Abbreviations

Table 1. *Some definitions and frequently used abbreviations*

ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
CAN	Controller Area Network
CRF	Calibrated Route Finder (*Krönt Vägval*)
CTI	Central Tyre Inflation
CTL	Cut-to-length (*sortimentsmetoden*)
Cu	Curvature (m^{-1})
EUR	Euro, €. 1 EUR = 9.8 SEK, 18 Dec. 2016
Fc	Fuel consumption (ml and litres/100 km)
G-VRP	Green Vehicle Routing Problem
GPS	Global Positioning System
Gr	Gradient (%)
GVW	Gross Vehicle Weight
Ig	Integrated gradient (%)
IRI	International Roughness Index
KV	Krönt Vägval (*Calibrated Route Finder in Swedish*)
LIDAR	Light Detection and Ranging
LKF	County, municipality, parish (*Län, Kommun, Församling*)
m^3sk	Cubic metres total volume over bark, from stump to tip (*skogskubikmeter*)
m^3sob	Cubic metres solid over bark (*fastkubikmeter på bark*)
m^3sub	Cubic metres solid under bark (*fastkubikmeter under bark*)
MC	Minimum Cost
MCDA	Multi Criteria Decision Analysis
NVDB	Swedish National Road Data Base (*Nationella vägdatabasen*)
PCA	Principal Component Analysis
R^2	Coefficients of determination
Rc	Functional road class
Rsr	Road surface roughness (mm/m)
SDC	Information hub for the Swedish forest industry (*Skogsbrukets Datacentral*)
SEK	Swedish currency, Crowns
SNVDB	The forestry sector road data base (*Skogliga nationella vägdatabasen*)
Sp	Speed (m/s)
t	Tonnes (metric)
VIF	Variance Inflation Factor
Wt	Weight (tonnes)

1 Introduction

Transport of forest raw material over long distances by logging truck is costly. Today, transport accounts for more than 25% of the Swedish forest industries' roundwood procurement cost at mill gate (exclusive stumpage), and the total cost of transport and management of forest roads is approximately the same as the total costs for the harvesting operations (Brunberg, 2016). Transport costs are likely to increase in the future, due to longer transport distances caused by structural changes in the industry, and higher operating costs due to increased fuel costs and other environmental concerns around, for example, CO_2 emissions. Swedish export-oriented forestry is facing tough competition on the international market, so more innovation and research are needed on efficiency improvements in the transport sector.

At the operative level, the task of the transport planner is to solve the logistical challenge of matching the need for raw materials in the industry with the availability in forms of harvested volumes of assortments in the forest. The raw material must be transported, mostly by truck, from the landing in the forest to the recipient point, usually a saw or pulp mill, or a heating plant.

A key issue is to find the best route, based on a balanced judgement of several criteria such as distance, driving time, fuel consumption, wear on truck, road safety, and working environment (Figure 1). Routes need to be selected and distances measured in, for example, major strategic decisions about material flow management (including location of terminals and mills), via the decisions on tactical level, down to the operational planning of the everyday work to deliver the raw material to the mill or heating plant.

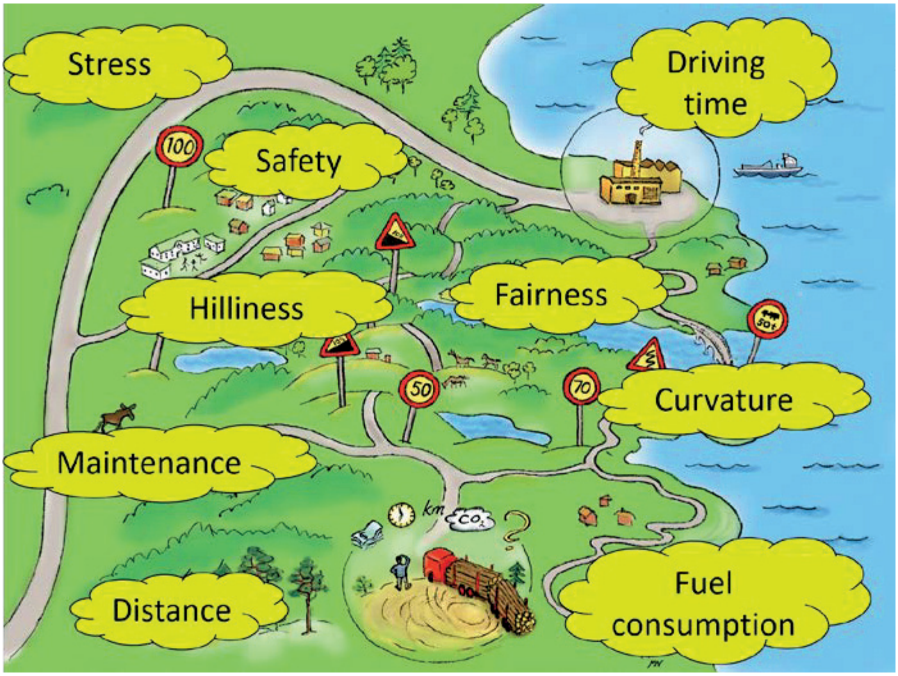

Figure 1. The task of deciding the best route from landing to industry is difficult, as it involves balancing both qualitative and quantitative objectives. Illustration: Margareta Nilsson.

Truck transport in the forestry sector is paid according to the size of the payload, measured in tonnes (metric tons). The remuneration consists of two parts – a fixed part per assignment, and a variable part determined by the distance between landing and recipient point.

Historically, several manually managed systems have been applied in parallel, which caused problems for hauliers working simultaneously for different forest companies. In an attempt to resolve the issue, the forestry sector has collaborated to develop a new, standardized, and more efficient system. The result was the Calibrated Route Finder (CRF) that, based on given prerequisites, automatically generates the best route and calculates the distance. The system was introduced by SDC, the common information hub for the Swedish forest industry, in 2009, and all major forest companies are now connected. The system is continually evaluated by the users, who report data errors and request improvement through a deviation report process.

Some deviation reports indicate that CRF chooses routes with too much hilliness and curvature, increasing both journey time and fuel consumption. Hilliness and curvature also increase a stressful working environment. The current version of the system may also propose turns at intersections that are either illegal or impossible for practical reasons. To address these issues, models must be developed that describe possible turns accurately and show how fuel consumption and operating speed are affected by road geometry and topography. There is also scope to improve the road data network on which CRF operates. This would also enable the system, when generating routes, to consider the increased time and fuel consumption caused by deceleration, waiting and acceleration associated with intersections.

1.1 Objectives

The objective of this thesis is to analyse and evaluate possible improvements of the Calibrated Route Finder for logging truck route generation. Three goals were to:

1. Describe how fuel consumption and operating speed for logging trucks are influenced by road characteristics, such as gradient, curvature and surface roughness, and truck weight.
2. Develop techniques to establish numerical weights describing curvature and hilliness, and evaluate how these weights affect route selection and distance on a national level.
3. Develop an augmented network to address issues relating to illegal and impossible turns in intersections, including detailed descriptions of time and fuel consumption.

2 Structure of the thesis

A key area for Skogforsk activities is research, development and implementation within the forest transport sector. The aim is to increase efficiency, reduce costs and the negative environmental impact. This work is often done in close cooperation with other organizations in Sweden, as well as international organizations in, for example, Finland and Canada. During the past decade, Skogforsk has been conducting studies and analysis of heavier and longer truck combinations, lower truck tare weight, improved scales, logistical solutions to integrate truck and railroad transport, and reduction of fuel consumption, and thereby emissions, though, for example, aerodynamic improvements.

Forest roads have also received much attention in terms of planning, construction and maintenance. Technical solutions to reduce road wear using tire pressure control systems (CTI) have been tested and analysed. Systems such as FlowOpt and RuttOpt has been developed and tested to support planning at different time horizons. To support distance calculations and route selection between forest and industry, the Calibrated Route Finder (CRF) has been developed.

CRF is a system for distance measurement collaboratively developed by the forestry sector. It uses best-practice routes, ‘key routes’ defined by the end users as the optimal solution in an inverse optimization process, to balance both qualitative and quantitative objectives. CRF is owned and managed by SDC, and both the CRF board and the Council for Forest Logistics are involved in decisions regarding development and implementation. CRF has been continuously developed since it was brought into practical operation in 2009. Developments include new weight settings, new and improved key routes, testing and implementation of new software for the basic routing algorithms to run on, and routing for trucks with different GVW.

The work within this thesis was limited to two improvements:

1. Papers I-III: The inclusion of features for curvature and hilliness to incorporate their influence on route selection and improve the estimations of fuel and time consumption.
2. Paper IV: The inclusion of turning restrictions, which enables estimation of increased fuel and time consumption in intersections. The latter has necessitated the development of an augmented road data network.

In Paper V, the work in Papers I-IV is summarized and placed in the full context of CRF, both regarding development and system implementation.

2.1 Development of curvature and hilliness

This development has followed two broadly parallel paths:

1. Paper I and II: Detailed empirical studies of the effects of curvature and gradient on operation speed and fuel consumption for a logging truck.
2. Paper III: Inclusion of curvature and hilliness in CRF based on existing knowledge of the effects of curvature and gradient. When results from Paper I became available, these were used to improve older data.

Data in NVDB is sometimes incorrect and sometimes lacking, so various methods for improving or supplementing the data were tested and implemented. These methods included using high resolution data from LIDAR and detailed road measurements from Paper I, filtering and spline functions.

Based on this improved data, the curvature feature was established by using the x,y-coordinate sequence describing the road geometry in the plane. For each coordinate, a curve radius was generated using adjacent coordinates. This curve radius was then used to calculate a maximum speed at which a truck could negotiate that curve, using a function developed by the Swedish Transport Administration. On road section level, the increased time consumption in relation to a straight road section was calculated and classified, based on posted speed limits and the required deceleration and acceleration.

The method involved establishing and classifying hilliness used the z-coordinates describing road position in terms of height in NVDB. All gradients between z-coordinates were calculated and divided by the length of the road section. This average gradient was then classified in relation to improved estimations of fuel consumption under Swedish conditions, using information from both existing models and new empirical data from this project. It is important to note that neither of these estimations provide accurate measurements of curvature or hilliness; instead, the aim was to classify road segments in order to assign weights for these attributes through the subsequent inverse optimization process.

2.2 Development of an augmented road data network

Turning restrictions in intersections needed to be managed better, to avoid routes that included illegal or impossible turns. The inclusion of such turns is an effect of using Dijkstra's algorithm (or similar algorithms) for the minimum-cost route problem in the basic road data network, where nodes and arcs are directly generated from road segments in the national road database NVDB. When the minimum-cost route is constructed in each node of the network, the information on how a truck reaches such a node is never considered in the algorithms. This implies that the basic network cannot be used to enforce turning restrictions.

The expansion of the basic road data network into an augmented network aims to eliminate this limitation. This was done by introducing additional nodes and arcs in the network, so that lanes in opposite directions are kept separate, and so that each turning alternative is represented by its own arc.

The proposed methodology for constructing an augmented network makes it possible to generate routes that follow all rules with regards to turning, i.e. ignoring forbidden and impossible turns by removing arcs representing illegal turns and acute angles between roads in intersections. An augmented network also makes it possible to include the effect on time and fuel consumption in intersections. In this case, models describing fuel and time consumption from Papers I and III were used, together with posted speed limits and average speed depending on road class.

Qualitative and quantitative evaluation of the features describing curvature and hilliness, and the augmented road network, was carried out using reference transport materials. These materials, representing both regional and national level, were supplied by both SDC and the forestry sector.

2.3 Additional tasks

Since 2012, I have been responsible at Skogforsk for the continuous development and implementation of CRF, both on practical and strategic level, in close cooperation with SDC. The work has included regular meetings with the CRF board and close cooperation with the Swedish Transport Administration to develop and improve data about the Swedish road network, and managing the expansion and refinement of the set of key routes together with the forest companies. The position, as a link between the forestry sector, external consultants (mainly Patrik Flisberg and Mikael Rönnqvist), and other organizations, has contributed in the development and implementation of the system.

Everyday tasks also involved dissemination of results, and involvement in evaluation and analysis of various improvements to the system and their consequences for forestry transport distances, costs and performance. This evaluation and analysis was often carried out directly with the end users, external consultants, and software companies. Current work includes development and analysis to manage winter roads far from the road network in northern Sweden, handling deviations relating to narrow roads, and an improved remuneration system that better reflects the actual work performed by the logging truck.

I have disseminated my research by presenting papers, written alone and together with other authors, on several occasions. The presentations and papers at international conferences listed below are in addition to Papers I-V:

FEC – Forest Engineering Conference

– *The Impact of Road Characteristics on Fuel Consumption for Timber Trucks.* Innovation in Forest Engineering: Adapting to Structural Change: Official Proceedings (Extended Abstracts) of the 4th Forest Engineering Conference. White River (South Africa), 2011

HVTT - Heavy Vehicle Transport Technology

– *The Influence of Road Characteristics on Fuel Consumption for Logging Trucks.* Stockholm (Sweden), 2012

– *The Impact of Road Geometry and Surface Roughness on Fuel Consumption.*

– *Calibrated Route Finder, an Objective and Efficient Agreement on Transport Distance.* San Luis (Argentina), 2014

– *The Impact of Road Geometry and Surface Roughness on Fuel Consumption and Operating Speed for Swedish Logging Trucks.*

– *Development and Implementation of New Features in a Route Selection and Distance Measurement System.* Rotorua (New Zealand), 2016

http://road-transport-technology.org/conferenceproceedings/

Precision Forestry Symposium

– *Calibrated Route Finder, an Objective and Efficient Agreement on Transport Distance Between Haulers and Customers.* Stellenbosch (South Africa), 2014

TRA – Transport Research Arena
– *The Impact of Road Geometry and Surface Roughness on Fuel Consumption for Swedish Logging Trucks.*
Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment. Paris (France), 2014

EEAP - EURO Excellence in Practice Award
– *Calibrated Route Finder – for Improved Transport Efficiency.*
Selected as one of six finalists in EURO Excellence in Practice Award. Glasgow (Scotland), 2015

SSFAR – Symposium for Systems Analysis in Forest Resources
– *Calibrated Route Finder, Use and Practical Experiences.* Uppsala (Sweden), 2015

FORMEC - International Symposium on Forestry Mechanization
– *Development and Implementation of New Features in a Route Selection and Distance Measurement System.* 48th International Symposium on Forestry Mechanization: 'Forest engineering: Making a positive contribution'. Linz (Austria), 2015
– *The Impact of Road Geometry and Surface Roughness on Fuel Consumption and Travelling Speed for Swedish Logging Trucks.* 49th International Symposium on Forestry Mechanization: 'From Theory to Practice: Challenges for Forest Engineering'. Warsaw (Poland), 2016

Besides these activities, I have been involved in the preparation of papers presented at conferences by co-authors. This included preparation of presentation material such as films and slideshow for the winning contribution, Daniel H. Wagner Prize for Excellence in Operations Research Practice. Nashville (TN), 2016.

3 Background

Forestry is a major economic activity in Sweden. Forestry and forest products accounted for 10.5% of the value of Swedish exports in 2011 (Skogsstyrelsen, 2014) and for much of the Swedish net export revenue. Price competition from other countries is a constant threat on export markets for forest products, so it is important to continuously improve efficiency.

Forestry is also very important to Sweden in terms of employment; in 2013, 15,000 people were directly employed in forestry and approximately 72,000 were employed directly by the forest industries (Skogsstyrelsen, 2014).

The forestry sector has developed significantly since the 1950s (Figure 2). All harvesting and transport operations are now mechanized. In harvesting, saw and axe were replaced first by chainsaws and later by harvesters. Timber transport, previously involving horse-drawn carriages, sledges, and log driving, now involves forwarders and 24-metre timber trucks.

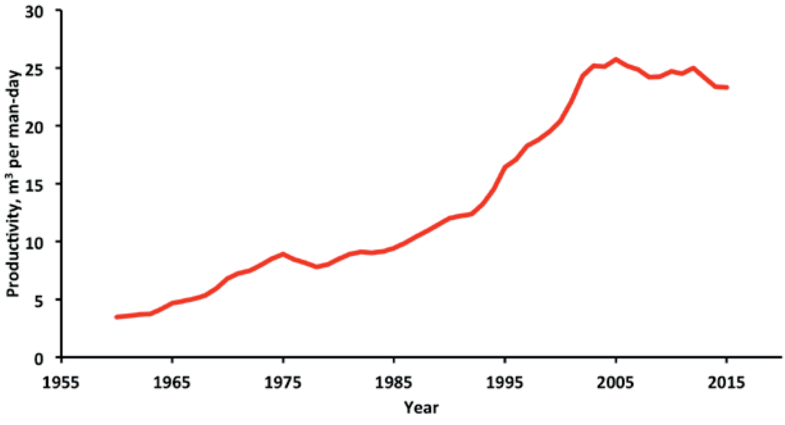

Figure 2. Productivity in Swedish forestry 1958-2015. Three-year average of m^3sk (total tree volume over bark from stump to tip) per man-day in forest work, including harvesting, terrain transport and silvicultural operations.

In Swedish forestry, large quantities of roundwood and forest fuels are transported from geographically dispersed harvest areas, so a well-functioning infrastructure is vital. Wood transport is a key part of the logistical system, and a crucial factor in the competitiveness of Swedish forestry. Long-distance road transport is costly; average transport cost is SEK 80/m^3sub (cubic metres solid under bark), equivalent to more than 25% of the forest industries´ total supply chain cost from their own forests to mill gate (Brunberg, 2016). Raw material from other forest owners or imported timber often has a higher total cost at mill gate, due to stumpage. In these cases, the transport proportion in total costs is smaller, but in absolute terms it remains at the same high level.

Despite some positive developments, such as lower tare weights, higher load weights and more efficient logistics, transport costs have increased rapidly compared to the consumer price index over the past decades, mainly due to longer transport distances and higher fuel prices (Brunberg, 2016), Figure 3. Equivalent experience has also been reported from other countries (Holzleitner *et al.*, 2011). If Swedish forestry is to remain competitive, and meet stringent requirements regarding greenhouse gas emissions, the transport system needs to be improved. This includes understanding several cost-affecting factors at different levels of detail, such as the impact of road geometry, topography and surface roughness on logging truck transport costs, and improved routing for operative, tactical and strategic planning.

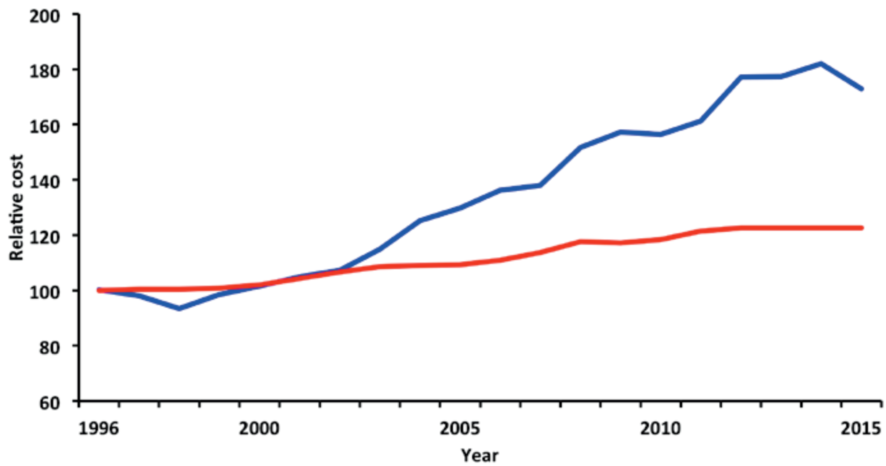

Figure 3. Transport costs (blue line) have increased more than the consumer price index, CPI (red line) since 1996.

The market has been demanding more precise deliveries, in terms of both volume and quality, for the past 10-15 years, and price competition from other materials and markets has toughened. For example, timber is under threat from concrete and plastic in construction of houses, and media developments have reduced demand for traditional newspapers in paper form. There is now greater pressure to differentiate the raw material according to its intended use, and to strike a balance between continuous and just-in-time supplies of fresh raw materials. There is also a need for greater capital efficiency and reduced wood stocks (Andersson and Westlund 2008).

3.1 Historical review

In Sweden, the cut-to-length system (CTL) has been dominant since the start of industrial forestry in the mid-19th century. All logs had to be handled manually, both in land transport and during log driving (Figure 4), so it was practical to buck the logs in the forest, normally to lengths between 2.7-5.5 meters. It also suited the industry and determined the design of today's logging trucks, which now transport mill-specific shortwood assortments directly to the customer (Fjeld & Dahlin, 2015).

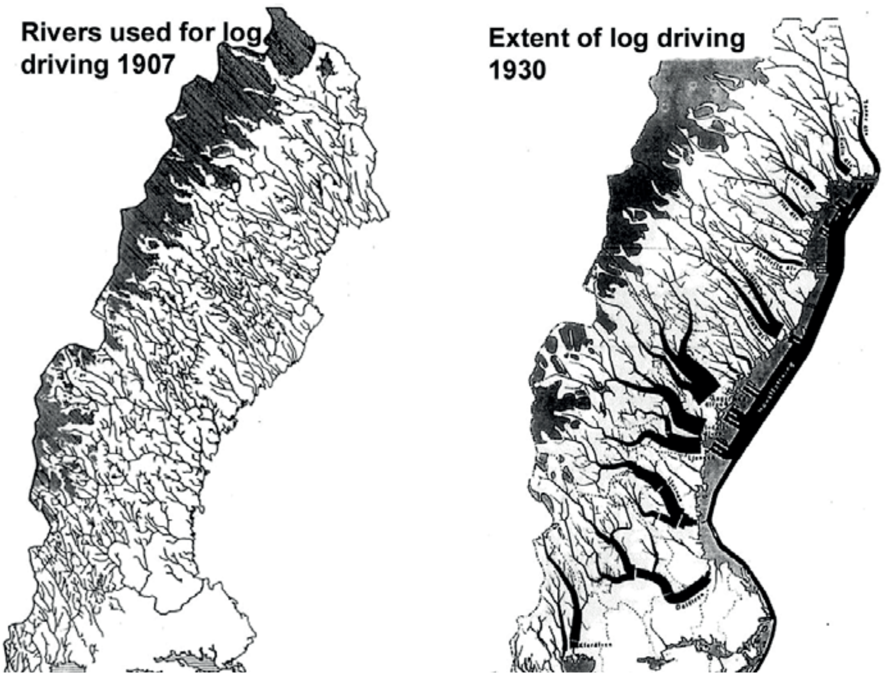

Figure 4. Left: Early 20th century main log driving watercourses in northern Sweden (illustration: G. Andersson); Right: timber flows in log driving watercourses 1930 (Nilsson, 1990).

In other parts of the world, like North America, mechanization started earlier, and heavy machinery was used from an early stage. Trees could be handled in full or long lengths, all the way from the stump to the mill, and a tree-length system developed. This also led to the different shapes of the logging trucks. In the Nordic countries, trucks often comprise truck and trailer, where the truck can transport one or two piles, and the trailer two or three, depending on assortment. Trucks in North America are often ‘piggy-back style’, where the short trailer supports the full tree length logs when loaded, and the trailer can be carried on the truck when unloaded. This improves traction on roads in steep terrain and allows smaller turnarounds in the forest (Sessions *et al.*, 2009).

Structural concentration of the Nordic forest industries to fewer and larger mills (saw, pulp and paper) has increased average transport distance, a trend that is expected to continue. In 1970, average transport distance in Swedish forestry was 66 km, compared to 90 km today. In 1970, log driving still accounted for almost 14% of total transport work (tonne-km), down from almost 58% in 1954 (Skogsbrukets Motortransportkommitté, 1972) cited in (Larsson, 1974). Trucks transported 54.6 million tonnes of timber in 1970, and log driving was used for 4 million tonnes, mainly for longer distances. In the period from 1954 to 1970, the total amount of wood transported increased from approximately 28 to 64 million tonnes. Most of this increase involved truck transport, and only a small proportion by rail. Log driving halved during this period, and disappeared completely as a means of transport in 1991 (Nilsson, 2007).

3.2 Transport of roundwood today

In Sweden, more than two million forestry transports take place each year. All forest raw material is transported by truck for at least a part of the journey from landing in the forest to the recipient point. Truck is preferable to rail mainly due to its flexibility, the limited access to railway, and the relatively short transport distance to the mills (Figure 5). Most of the volume is transported directly, but terminals are also used for intermediate storage and for transfer to rail.

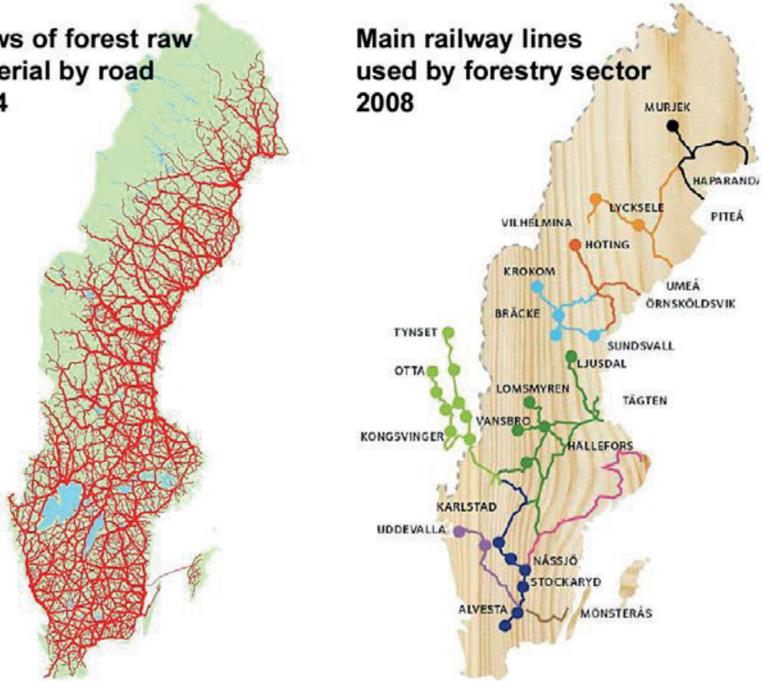

Figure 5. Left: Flow of forest raw material by truck from forest to mill in Sweden. Source: Skogforsk. Right: Main railway lines used today by the forestry sector. Source: The Swedish Forest Industries.

The average transport cost for all assortments is SEK 80/m^{3}sub. The cost for spruce saw logs is SEK 78-82/m^{3}sub, for pine saw logs SEK 71-81/m^{3}sub, and for coniferous pulp logs SEK 77-80/m^{3}sub (Brunberg, 2016). Annual total transport costs for forest raw material are around SEK 6 billion.

Pulp mills consume larger volumes of raw material from larger geographical areas than saw mills, so transport distances for pulp mills are often longer than for saw mills. Average truck transport distance loaded from landing to mill is 105 km for pulp wood and 93 km for timber. The average truck transport distance for forest fuels, which are more sensitive to transportation costs and normally used locally, is 67 km loaded from landing to heating plant (Asmoarp & Davidsson, 2016). Average transport distance by truck for all assortments of roundwood and forest fuels is 91 km, and total truck transport work is 6.6 billion tonne-km.

Rail is competitive when large volumes are to be transported over long distances (Vierth *et al.*, 2008). As truck transport is often faster, railways generally handle goods with lower commodity values. Railway transport is common over longer distances, due to high capacity, both for roundwood, forest residues and finished goods such as paper. The present maximum axle weight on the Swedish public rail network is 22.5 tonnes, and is expected to increase to 25 tonnes (Fjeld & Dahlin, 2015). The maximum number of wagons per train is normally limited by the length of the receiving area at the terminal or mill.

In Sweden, approximately 15% of the total volume of roundwood is now transported by rail (Skogsstyrelsen, 2014). The proportion transported by rail increased after the severe wind felling in 2005, when industry realized the potential of rail transport. The trend towards greater rail transport is likely to continue, on both cost and environmental grounds.

Switches between modes of transport, intermodal transportation, can increase costs, for example due to handling of goods, increased time or travelling distance, but smart combinations that utilize the strengths of the individual modes could reduce the total cost, despite the extra handling (Flodén, 2007).

3.3 Logging truck transport technology

3.3.1 Truck dimensions

Today, the maximum gross vehicle weight (GVW) of a logging truck and trailer combination in Sweden is 64 tonnes, given a certain axle distribution (Transportstyrelsen, 2016). Length is maximized to 25.25 metres, but is normally 24 metres. Internationally, maximum GVW also depends on how different units are combined, such as tractor, truck, trailer, semitrailer, type of suspension, and number and type of axles. In the EU, maximum GVW for the largest combinations varies between 40 and 60 tonnes. In the US, federal regulations limit the gross weight to 80,000 pounds, i.e. 36.3 tonnes, while some state regulations allow up to 50 tonnes and more (Jacob & Cerezo, 2015). Sweden and Finland (76 tonnes) are exceptions from the EU regulations (Fogdestam & Löfroth, 2015).

Swedish restrictions on vehicle weight have changed over the past century. In 1907, in the first regulation on automobile traffic, the load on the road was regulated in relation to the width of the wheels, which had to be at least 8 cm. In 1917, regulations on wheel load were introduced, and in 1952, maximum GVW was regulated for the first time (33.5 tonnes). Maximum GVW has since gradually been increased according to the Swedish Code of Statutes, as shown in Table 2 (Holmstrand, 2011). The Swedish Government has proposed an increase in maximum GVW to 74 tonnes on a limited road network from 1 March 2017 (Regeringskansliet, 2016).

Although the maximum weight limits have increased over time, limitations occur in the road network, such as bridges and reduced GVW during spring thaw, meaning that the maximum GVW could not be utilized. This still applies in parts of the road network, and road bearing classes BK2-BK3 have a reduced maximum GVW.

Table 2. *Development of Swedish maximum permitted truck gross vehicle weight (GVW) and axle weights, given stipulated axle distribution and no bearing capacity reductions in the network*

	GVW	Single axle	Bogie axle	Tridem axle
1952	33.5	6	8	
1968	37.5	8	12	
1975	51.4	10	16	
1990	56	10	16	24
1993	60	10*	18 (19)	24
2015	64	10*	18	24

*11.5 tonnes on driven axle

Regulations regarding maximum vehicle width were introduced in 1907. The basic rule was that driving an automobile on a public road was only permitted if the road was at least 3.6 m wide. In 1924, limitations on vehicle width were introduced (210 cm) and, over time, this limitation has been gradually increased to the current 260 cm for trucks and 255 cm for buses. A regulation limiting maximum vehicle length to 24 metres was introduced in 1968, and for EU standard modules this was increased to 25.25 metres in 1997 (Transportstyrelsen, 2016).

3.3.2 Truck combinations

Two common types of truck/trailer combination are used in forestry today: self-loading trucks and trucks that work in groups and require a separate loader, Figure 6 (Fjeld & Dahlin, 2015). Loaders (a knuckle boom crane) can be removed from many self-loading trucks after loading, reducing vehicle weight during transport and allowing a larger payload. Trucks loaded by separate loaders are the lightest since they neither require the loader nor the extra hydraulics and extra components required to mount them (Table 3). The table also shows the 74-tonne self-loading truck, and the ETT 90-tonne truck currently undergoing extensive trials and demonstration in Sweden (Figure 7). The move towards even lower tare weight is the result of improved design and the use of lighter components and stronger materials.

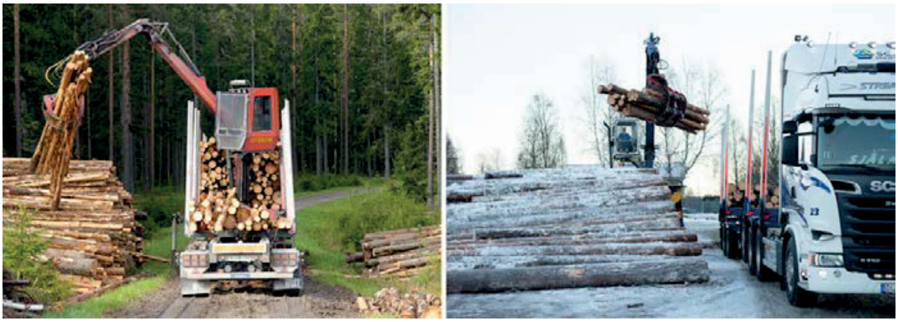

Figure 6. Two types of trucks dominate in Swedish forestry, self-loading trucks (left), and group trucks loaded by a separate loader at the landing (right). (Left photo, SKOGENbild, right photo, Erik Viklund, Skogforsk).

Table 3. *Examples of maximum payloads for different types of logging truck and trailer combinations, including the heavier and longer rigs currently being studied by Skogforsk. Figures in parentheses are examples of truck and trailer combinations where attempts are made to minimize tare weight.*

	Tare weight (t)	Max. payload (t)
Self-loading truck	22 (18.5)	42 (45.5)
Self-loading truck (without loader)	20 (16)	44 (48)
Group trucks (using separate loader)	18 (15.5)	46 (48.5)
ST 74 tonnes self-loading truck	24	50
ETT 90 tonnes truck (30 m, separate loader)	24.5	65.5

Figure 7. Two types of experimental trucks currently undergoing extensive trials and demonstration in Sweden. Left, a 74-tonne GVW self-loading truck with 9 axles and, right, the ETT 90-tonne GVW truck, with 11 axles distributed over the vehicle's total length of 30 metres. (Left photo, Niklas Fogdestam, right photo, Per Pettersson).

Self-loading trucks have loaders mounted on the back edge of the truck. The trailers are often equipped with sliding platforms so that the stakes at the rear part of the trailer can be loaded at the front (i.e. closest to the loader) and then slid to the back, before loading the rest of the trailer. The configurations using separate loaders require large transport volumes per site, and 5-7 trucks may work together in groups at distances between 30 and 150 km from forest to recipient point or mill. These groups require larger landings to accommodate both the loader and truck beside each other.

Vehicle technology is adapted to transport timber from the peripheral branches of the road network. Even though the proportion of private roads during an average assignment is only 4% (Andersson & Frisk, 2013), the trucks must be designed in such a way that they can be driven under the worst conditions. This involves, for example, strengthening the truck structure and using more drive axles (Carlsson & Rådström, 1987). The downside of this is heavier and more expensive vehicles with lower payloads and higher fuel consumption, which increases transport costs compared to if the roads were of a higher quality. Particularly serious is the reduced payload, a factor that has a major impact on the transport cost.

According to Carlsson and Rådström (1987), roads are generally of poorer quality in southern Sweden, which increases transport costs due to higher tare weight and lower payload. Poor road conditions may also prevent the rig being driven all the way to the landing; sometimes the trailer must be left on the higher-quality road, and only the truck is used to pick up the timber and then reload onto the trailer. This greatly extends the time taken to load an entire rig (Carlsson & Rådström, 1987). Poor road conditions are often caused by deficiencies in the geometric standard, like alignment, turning space and road connections.

Tire Pressure Control Systems (TPCS), such as Central Tire Inflation (CTI), are a way of adapting the truck to bad road conditions. CTI enables the truck driver to quickly reduce and increase tire pressure (Granlund, 2006; Scottish Entreprise, 2003). When the pressure in the tires is lowered, they become flattened, increasing the contact surface with the road, reducing the pressure on the road, and increasing traction (Granlund & Lang, 2016). The system was initially developed to increase traction on soft soils like sand, but has also proved advantageous in logging transportation. Tire pressure is adapted to the actual need depending on road condition, which normally means higher pressure on paved roads and lower on gravel roads. The system is particularly useful during wet or thawing periods, when the road surface is soft and the risk of damage from heavy trucks is increased. Under such circumstances, lower tire pressure reduces these risks. Low-pressure tires can reduce fuel consumption, as well as giving a smoother and safer ride (Bradley, 2009; Munro & MacCulloch, 2008).

Another way of managing varying road conditions is customized truck and trailer combinations for different parts of the assignment (Montgomery *et al.*, 2016). In the ETT project, adapted vehicles for the various transport parts were tested; reinforced vehicles are used for forest road transport from the landing in the forest to a trans-shipment place at a public road, where vehicles adapted for road transport drive the wood the long distance to the recipient point (Löfroth & Svenson, 2012). These vehicles had higher payloads due to a simpler construction and because they did not need to carry a crane. Investment cost was lower, and the driver needed no training in crane operation. Furthermore, these combinations consisted of tractor and trailer, and the tractor and driver could be called in from other types of transport assignments, thereby increasing flexibility and utilization.

The system of using two different combinations for separate parts of the assignment lowered fuel consumption and increased payloads, and the system was found to be beneficial under certain conditions. However, the logistical challenges became too difficult for the system. A similar trial was carried out in Scotland, where specially designed trucks were used to increase payload and reduce road wear (Scottish Entreprise, 2003). Trials based on the same idea, i.e. using customized combinations for different parts of the transport assignment, have been carried out by the timber haulage company VSV Frakt in southwest Sweden. Load racks were also used – simplified containers for timber transport – to reduce terminal time.

3.4 Transport cost calculation

Sundberg and Silversides (1988) divide the costs related to the transport system into two parts, variable and terminal (fixed) costs, which can be either direct or indirect (Sundberg & Silversides, 1988). Direct costs are charged directly to the specific load, whereas indirect costs are broader, not necessarily only relating to forest raw material. In Table 4, these costs are allocated to three work components.

Table 4. *Work and cost components in the transport system defined by Sundberg and Silversides (1988).*

Work component	Cost component
Planning, supervision, control and administration	Overhead cost of transport
Movement of goods:	
over a distance	Variable direct cost
at terminals	Terminal (fixed) direct cost
Installations:	
transport routes	Variable indirect cost
terminals	Terminal (fixed) indirect cost

To accurately predict transport costs, detailed costing calculations must be carried out. This information is also important in transport price negotiations. The calculation method used can vary with the situation, but all models are based on yearly cost statistics (Fjeld & Dahlin, 2015). The approximate distribution of annual costs for a three-axle forest truck with a four-axle trailer is shown below (Table 5). The main difference between costing models is whether capital costs are treated as a fixed or a variable cost. After calculating the costs, a suitable profit margin must be added (as a proportion of costs) to obtain the price of the service.

Table 5. *Typical distribution of annual costs for a forest truck and trailer combination (Statistics Sweden, 2016).*

Cost class	Cost item	% of annual costs
Fixed costs (per operating hour)	Interest	1.1
	Tax, insurance	0.7
	Administration	6.0
	Personnel costs	35.8
Variable costs (per km)	Diesel	31.2
	Value depreciation	12.5
	Repairs, service	9.2
	Tire wear	3.5

A typical tariff for roundwood transport is based on a terminal (fixed) part per tonne, and a variable part per tonne. The fixed part covers terminal handling, like loading in the forest and unloading at the recipient point, and the variable part the transport to and from the forest (Sundberg & Silversides, 1988). As each assignment has both a terminal and a variable distance cost, short-distance assignments are more expensive per kilometre than long-distance assignments.

For each assignment, both the distance and the payload must be measured. The dominant measure in forestry transport is weight (tonnes) because of the weight limitations on transport infrastructure (Fjeld & Dahlin, 2015). Most pulp mills have scales and the haulier is paid by the weight shown. Most sawmills still use volume measurement as the basis of remuneration, a volume that is converted into tonnes on the basis of several factors, such as the mass proportion, assortment and time of the year.

In most cases, each haulage company has its own agreement with each forest company they have as customer. Typical remuneration to the haulier for the fixed part is SEK 20/tonne, and for the variable part SEK 0.5/km, but the individual levels can vary. Normally, the variable part is the same for both short and longer distances but, in some cases, there is an adjustment for longer distances, for example over 100 km one way.

The level of the fixed and variable remuneration is influenced by factors affecting hauling productivity. Depending on the factor, either the fixed part or the variable part, or both, can be affected. Factors that can be used to alter remuneration levels, determined in annual negotiations between haulier and forest company, include the following:

Average transport distance. The longer the average transport distance, the greater the proportion of the transport that is probably on roads of higher-quality public roads, road class 0-6. This enables the haulier to maintain a higher average speed on assignments. Naturally there are variations and exceptions, such as when the assignment involves a long distance from the landing to a public road, or where the public roads are of low quality, for example, narrow and winding with a gravel surface.

Proportion of forest roads. The higher the proportion of forest roads, the lower the average speed, and the fewer the assignments that can be completed during a shift or during a year.

Opening hours at the recipient points. The longer the opening hours at the mill, the more choices for efficient route planning and the shorter the waiting time for unloading.

Waiting time at the recipient points. At some mills, reception capacity is insufficient for peak deliveries, for example on Monday mornings. After a certain waiting time, time compensation applies, but the haulier still loses productivity.

Topography of the area. The more difficult the topography, the higher the fuel consumption and lower average speed for the operator.

Proportion of urban traffic and other obstacles. Driving in urban environments lowers the average speed, increases fuel consumption, and increases stress on the driver.

Assortment composition. Some assortments are more difficult to handle, and others may not give full loads (due to volume restrictions) under certain periods (often summer).

Percentage of delivery timber. Delivery timber originates from small forest property owners, and are often smaller piles of different assortments. This affects the number of visits to landings for a haulier during a year. Collecting small volumes from several landings during a run means increased terminal time as the driver must go through all stages of loading at each landing.

Back haulage. If loading rate can be increased, the haulier can increase efficiency. Remuneration can be based on either a gross or net list, where the gross list expects no back haulage. The gross list entitles the haulier to a higher remuneration per tonne, but remuneration is reduced where and if back haulage is possible. The net list constitutes a certain part of back haulage.

3.5 The Swedish road network

The forest sector is dependent on the forest being available for various activities, which requires high-quality roads. The average distance between forest and industry is 90 km. Since virtually all the annual cut of raw material, 70 million m^3sub 2013 (Skogsstyrelsen, 2014), is transported by truck for some of this journey, roads on both the public and private networks have come to play a significant role. The quality of the roads is crucial to ensure a steady flow of raw materials of high quality and to enable the Swedish forest industry to produce competitive products.

The Swedish road network is almost 580,000 km (Table 6). The roads are either public, under the responsibility of the state or municipality, or private, managed by private land owners, often organized in road communities (Sandberg, 2011). Certain private roads are eligible for state (and sometimes also municipal) grants for road maintenance, normally 60% of estimated operating cost (Grönvall, 2007).

Table 6. The Swedish road network consists of both public, municipal and private roads.

Road holder			
Government			98000 km
Municipal			42000 km
Private			436000 km
	with government grant	74000 km	
	without government grant	362000 km	
Total network			577000 km

High-quality roads are required for accessibility, availability and road safety. From an economic perspective, it is also important to maintain even low-traffic roads through an effective operation and maintenance strategy. Overlooking maintenance leads to higher costs later. Forest road maintenance requirements have increased over time. Forest raw material is now transported all year around, at a higher intensity and with larger trucks, meaning higher axle loads and shorter recovery times between passing loads. Transport also takes place under wet or thawing periods (Scottish Entreprise, 2003), and heavy rainfall can cause problems, particularly on the private roads.

Both the public and private road networks may suffer from bearing capacity restrictions during the spring thaw period. Bearing capacity problems can be overcome by building up stocks, but this is costly for several reasons, for example increased transport distance, more handling and wood quality deterioration (Arvidsson & Holmgren, 1999). In 1990, 58% of the public road network had all-year maximum GVW bearing capacity (at that time 56 tonnes), i.e. including spring thaw periods, but only 5% in the private road network (Skogsstyrelsen, 1991).

The forestry sector is continuously improving forest roads to meet the demands for efficient logistics. In 2008, the additional cost for the forest industry due to shortcomings in bearing capacity in the public road network was estimated to be up to SEK 650 million. This is expected to increase in the future due to increased logging volumes and a warmer climate (Andersson & Westlund, 2008), and there is a risk that the bearing capacity problem will exacerbate if no action is taken. The public network is the only connection between the forest roads and the recipient industries, so a high standard is vital to the supply of raw material from the forestry sector.

Vägplan 90, prepared by the Swedish Forest Agency, described the condition and extension plan of the road network in 1990. "Incentives for building forest roads are strong. There is no realistic alternative to road transport, either now or in the foreseeable future. Where forestry takes place under the conditions defined by the market and society, access to forest roads is required" (Skogsstyrelsen, 1991). Transporting timber through the forest with forwarders costs in the order of 50 times more than the same distance on road. Carbon dioxide emissions are also accordingly greater.

The private road network expanded rapidly during the 1970s and 1980s and, by 1990, 68% of forest land was within 500 m of a road. Average road density on productive forest land in 1990 was 16 m/ha, with a variation from 26 m/ha in southern Sweden to 10 m/ha in the north.

Forest roads are built to meet both a certain bearing capacity and geometric standard, with the latter varying according to, for example, sight and stopping distance. Most of the forest roads in Sweden are of Classes 3C and 4C, where the design speed for a truck and trailer combination is either 30 km/h (Class 3) or 20 km/h (Class 4). The normal bearing capacity on forest roads is Class C, which stipulates that logging trucks should be able to use these roads all year around, except during spring thaw and intensive and extended rainfall. Roads with higher bearing capacity are also better at withstanding the more intense traffic, because the recovery time for the road between repeated strains from fully loaded trucks is shorter than normal (Fjeld & Dahlin, 2015).

All Swedish roads are described in NVDB, the Swedish comprehensive digital road database. Construction of the database began following a government directive in 1996, but the idea of constructing a digital road database for different planning purposes had been initiated by the forestry sector already in the 1980s when distance measurement was tested on digital maps. This development continued during the early 1990s with the construction of digital databases. Transport planning was based on these, and the positive results from the forestry sector accelerated the national initiative to compile such a database.

From the very beginning, the idea was that NVDB would contain information about the entire Swedish road network. The aim was that the information would be compiled and stored in one place and that all information would be quality assured. The motive for the road database was that the information would be used in, for example, transport planning and navigation. NVDB is managed by the Swedish Transport Administration, which is responsible for quality assurance and operation. NVDB is a collaboration between the Swedish Transport Administration, the Swedish Association of Local Authorities and Regions, the Swedish Mapping, Cadastral and Land Registration Authority, and the forestry sector. The forestry sector is responsible for data collection and maintenance of all private roads, which constitute more than 80% of the total road network in Sweden (Flisberg *et al.*, 2012).

In NVDB, the road network is described in the form of road segments (arcs) and how they extend through the landscape. The arcs are linked through nodes. Road geometry is described by x, y and z-coordinates, where z is the vertical and x and y the horizontal coordinates. Road and traffic characteristics are described for each road segment, such as road manager, posted speed limit, bearing restrictions, road width, and many more. The road network is divided into functional road classes, ten in number, which describes the significance of each road in facilitating connections in the network. Road classes 0-6 are public roads, and 7-9 private roads. Road classes 0-2 comprise European motorways and major roads, while road classes 7-9 are often forest roads.

The forestry sector does not normally use NVDB directly in everyday operation, but rather the sector's own version, SNVDB. This database contains information from NVDB, but is supplemented by information about special forestry attributes, such as turning alternatives at the end of roads in forests, suitability for different truck combinations, timber routes (i.e. forest roads designed for large traffic volumes), passing routes that direct the traffic around and not through city centres and other vulnerable areas, and approach routes that direct the traffic to a certain recipient point. The difference between the latter two is that a passing route can be travelled in two directions, and can be used and then left, whereas an approach route is unidirectional, ending at the recipient point, and vehicles cannot leave the route. The objective of both these types of routes is to avoid road safety sensitive areas, such as near schools.

3.6 Wood flow management

The logistics system has developed over time, from trading on the local market, to a global system characterized by specialization and customer orientation. The forestry sector has evolved in the same way and, in combination with the challenges of a divergent material flow, this places great demands on the logistics system (Fjeld & Dahlin, 2015). Much of the solution to this challenge is in design, planning and monitoring of the supply system, which must match industry requirements for volumes and assortments with harvesting operations in the forest.

The actual flow of logs from landing to mill is a result of many decisions made at different levels. Planning the wood flow can be divided into strategic, tactical and operational levels, characterized by different time spans and degree of centralization (D'Amours *et al.*, 2008). The strategic level comprises the development of the logistical system (rail and road transport in relation to mill supply commitments and available harvesting volumes), and the tactical level, which concern planning from one week to one year, involves wood flow planning within the restrictions of the chosen transport system (Frisk *et al.*, 2010; Carlsson & Rönnqvist, 2007). Normally, responsibility for operational planning, i.e. arranging transport from the landing to the recipient point, lies with the wood supply organizations, as they control harvesting plans and operations (Fjeld & Dahlin, 2015) and this is supported by specialized software (Flisberg *et al.*, 2012; Flisberg *et al.*, 2009). Forest companies have their transport managers, and larger haulage organizations employ their own geographical coordinators to monitor operations Several decision support systems are available for transport planning on strategic, tactical and operative level, both for supporting coming decision making and for analysing completed activities. (Frisk *et al.*, 2016; Flisberg *et al.*, 2014; Andersson *et al.*, 2008; Forsberg *et al.*, 2005).

One effective way to reduce transport costs is barter of comparable assortments between forest companies (Fjeld & Dahlin, 2015; Frisk *et al.*, 2010). According to these authors, barter is in three main forms:

- Exchange between geographical areas. This takes place when one enterprise's forest is far from its industrial customer, and another enterprise's forest is closer. The aim here is to reduce transport work.
- Exchange between periods. This takes place when one enterprise has a periodic surplus and another enterprise a periodic deficit. The aim is to reduce storage.
- Exchange between assortments. This takes place when one enterprise has a surplus of a specific assortment and another a deficit, with the aim is to obtain the right qualities for industrial processing.

Average transport distance to supply a mill is a result of factors such as annual wood consumption, the availability of the right assortments in the supply area, and competition. Increased wood consumption often increases average transport distance considerably (Fjeld & Dahlin, 2015). Given a defined wood consumption and average transport distance, the transport capacity can be calculated. If an improved routing can mean higher average speed, the transport capacity requirements can be reduced, providing the transport distance is unchanged.

Transport capacity needs vary over the year. Normally, the need is greater during winter time when the timber has its highest density (no drying to reduce the weight). As maximum load is (normally) restricted by weight, this means that the average load is smaller in terms of volume during the winter. Spring thaw periods and fluctuations in forest industry demands also affect transport needs. Transport capacity needs can also vary from year to year, for example due to storms.

Many logging trucks are equipped with vehicle computers that enable contact with the transport base. This improves performance and increases the range of the vehicle fleet. With navigation support in the cabs, trucks are more flexible and are not so tied to their home areas, and the driver can quickly and easily find the way between the landing and the industry, especially if they are in an unknown area. Transport capacity can therefore be switched between different areas and deployed where there is most need for capacity, which enables a smaller and more efficient vehicle fleet.

Accurate information is needed about the road status in order to benefit from navigating using a vehicle computer (Ekstrand & Skutin, 2005). These authors found that the availability of information on the conditions of navigability and the size and content of roadside stock is the most critical factor in increasing transport chain efficiency. Implementation of vehicle computers increases the demand for accurate information, so it will drive development towards better reporting from previous links in the chain, i.e. forwarders. Transport efficiency can be further improved by making use of the tools already available, such as Calibrated Route Finder, and by constantly testing and developing new planning tools. SNVDB is, and will continue to be, a cornerstone of many of these planning tools.

4 Reducing transport costs

Transport of forest raw material in Sweden costs more than SEK 80 /m^3sub (Brunberg, 2016), and with an annual cut of 70 million m^3sub (Skogsstyrelsen, 2014), this means a total cost of SEK 6 billion annually. The corresponding figures for long distance transport of roundwood in the forest industries and State forest Enterprise in Finland is EUR 8.91/ m^3sob (solid cubic metres over bark) (Strandström, 2015).

In January 2016, the shares of transport cost from wages and fuel was 37.1% and 28.6% respectively (Statistics Sweden, 2016). Corresponding proportions in Finland were 38-43% for wages, and 15-22% for fuel depending on material transported (Laitila *et al.*, 2016; Laitila *et al.*, 2015). If what is spent on roads each year, SEK 20-30/m^3sub, is added, this gives a total of SEK 7-8 billion or SEK 110-120/m^3sub. This means that the cost of transport and roads, up to one-third of the cost of raw materials delivered at mill gate, is roughly the same as the cost of harvesting.

Costs are likely to increase in the future. For example, we are already seeing longer transport distances due to structural changes in industry and increased operating costs due to rising fuel costs. Given how exposed the Swedish forestry is to competition on the international market, it is therefore very important to find ways to reduce costs of transport and roads.

Harvesting productivity has increased considerably since mechanization started in Sweden in the mid-20th century, mostly due to improved machine efficiency and machine utilization. There is less capacity for improving efficiency in the transport phase of the supply chain, as the maximum legal speed of a truck is 80 km/h, and machine utilization is already very high, but there is still scope for improvement. Almost two-thirds of Swedish transport cost consists of variable costs, fuel and wages, so work to reduce fuel consumption and turnaround time can influence transport costs considerably. Improvements in productivity, by increasing payload and load rate, also help to reduce transport costs. In the following section, ways to improve efficiency are presented.

Road transport is one link in a larger logistic chain to supply the mill or heating plant with the right assortments at the right time. Improving each link in that chain is important, but development of the parts must never be at the cost of the whole. Collaboration is essential – the transfer between different stages in the logistic chain must be as efficient as possible, and efficient collaboration is positive for profitability at every stage.

4.1 Road transport performance

One very important factor for logging truck productivity is the payload, which can be improved by increasing the maximum permitted GVW or lowering the tare weight of the trucks. GVW limits were raised in Sweden through the 20th century and, most recently, maximum GVW was increased from 60 to 64 tonnes in 2015. Research into and demonstrations of 74-tonne truck and trailer combinations within the length of 25.25 metres has been taking place in Sweden in recent years, as well as a 90-tonne and 30-metre truck combination. These new combinations have increased productivity by 37-56%, and reduced fuel consumption and transport costs by 7-20% compared to conventional 60-tonne trucks (Fogdestam & Löfroth, 2015). A scenario where 30% of roundwood is transported by 90-tonne vehicles, and 70% by 74-tonne vehicles would reduce the number of trucks on the road by 25% and CO_2 emissions by 10-15% (Andersson & Frisk, 2013).

Finland increased its maximum GVW to 76 tonnes in 2013, much inspired by the Swedish experiences, and other countries in Europe and elsewhere are considering both longer and heavier truck and trailer combinations. Improved bearing capacity in the road network, and fewer bearing capacity restrictions on bridges, will open more of the network to heavier trucks.

In addition to increasing maximum GVW, reducing the tare weight of vehicles is also positive for profitability. Each tonne in reduction can increase productivity by some 2.5%, increasing haulier revenues by more than SEK 100,000 per year (Löfroth & Nordén, 2003). Tare weight can be reduced by using lighter materials, such as higher-quality steel, replacing steel with aluminum, and using lightweight components where possible. Simplified construction and smaller engines also helps to increase payload, as well as removable self-loaders that, when left at the roadside during transport to the mill, increases payload by 2-3 tonnes. Reliable scales are also a way of increasing the payload, as they enable the driver to load the truck and trailer very close to the maximum GVW without risking illegal overloads (Siry *et al.*, 2006; Greene *et al.*, 2004).

The ETT project has shown that using the right vehicle on each assignment can improve productivity. Less than 5% of an average assignment is on low-quality roads (Andersson & Frisk, 2013), and the rest is on public roads, but the rigs must be equipped to endure the worst conditions, which makes them both heavy and expensive. Engine and truck equipment customized to local conditions to maximize productivity and minimize fuel consumption might be a solution, but there is a logistical challenge. Future self-driving vehicles will open new opportunities for efficiency improvements in different ways, and multiuse trailers that can handle different types of raw materials, such as roundwood, chips, forest fuels or other goods, can improve load rate and productivity.

Naturally, reduced fuel consumption is a way to improve efficiency, and many measures can be implemented such as purchasing vehicles with smaller engines, or improving aerodynamics, which Skogforsk has recently demonstrated (Löfroth, 2014a). Much fuel is wasted by square fronts and irregularities in shape, such as banks and stakes.

Fuel consumption varies much between drivers, and can be reduced by ecodriving training. This is an instant effect, but decreases with time. Onboard technology can both support and monitor improved driving patterns (McIlroy *et al.*, 2016; Schall *et al.*, 2016). Other ways to save fuel are ensuring tires have the right pressure, using low-rolling resistance tires, and reducing idling.

Normally, Swedish logging truck and trailers are equipped with twin tires. One way to reduce fuel consumption would be to mount super single tires instead. These are lighter and cheaper than a twin tire combination and cause less drag (Scottish Entreprise, 2003). However, super single tires generally cause more damage on forest roads because the ground contact is more concentrated. Another problem is that, if a super single tire is punctured, the truck must stop, unlike twin tires where, after a puncture, the vehicle can still be driven to the workshop for repair.

One possible risk is that investments in fuel saving techniques will partially be lost due to rebound effects when lower transportation costs stimulate the demand for trucking services (De Borger & Mulalic, 2012), or reduce the ambition for eco-driving.

4.2 Road network design

Road network design has a direct effect on transport costs, and a well-developed road network and greater road density reduces forwarding distance, and improves the productivity of the whole supply chain.

Planning, design, construction and maintenance can be improved to reduce the costs of both building and using roads. One important tradeoff to consider is therefore the one between investments in roads and transport costs (Della-Moretta & Sullivan, 1975). On roads with heavy traffic, investments in construction and maintenance can be justified by savings in vehicle operating costs, and vice versa. A major challenge in finding the optimal balance is to correctly assess the vehicle operating costs, time savings and safety. These are critical components in transport planning and investment decision-making processes. The marginal effect on vehicle operating cost is normally small when it comes to highly developed transport systems, but is much larger for less developed networks, where the connection between the road builder and the road user is closer. Forestry roads in remote areas is one example.

Improved road standard and maintenance levels improve performance and productivity by shortening cycle times and reducing fuel consumption and depreciation. High-standard roads can also extend the transport season to include spring and autumn thaw and rainy periods, and are accessible for a full rig. Where roads are of low quality, the driver must leave the trailer on a better road, and use the truck to collect the roundwood and move it to the trailer, a procedure that significantly increases handling at the landing.

To reduce costs in road management it is important to, for example, find the optimal layer thickness and use appropriate aggregate. Well-built roads need less time to recover after a truck passage. The use of CTI causes less damage to roads, and may allow a thinner gravel layer. Decision support systems, such as the Canadian Opti-grade and Vägrust from Skogforsk, can alert the road maintainer as to when and where to implement measures (Flisberg *et al.*, 2014).

4.3 Transport planning

Planning at strategic, tactical and operative level can improve productivity and reduce transport costs. At the strategic level, barter is common, and collaborative planning between the forest companies can reduce costs in the range of 5-15% (Frisk *et al.*, 2010). Terminals can also play an important role. Although terminals often increase handling costs and transport distance, they can be useful in multimodal transport; to increase load rate by back haulage, or when heavier and longer truck combinations are permitted on a part of the network.

Route selection, and thereby the distance to travel, is a combination of time and fuel consumption considerations, which in turn are affected by road conditions. The relationship between fuel and time costs changes over time; for example, fuel prices have increased proportionally more than other costs over the last decade. Therefore, to make accurate strategic and operative decisions, knowledge about the consequences of changes in these relationships is important.

Turnaround time can be shortened by better planned and organized landings in the forest, which decreases loading time. The landings must be placed along the roads at places that do not constitute traffic hazards, and the forwarder must unload the wood into stacks that are easy for the truck driver to load (Skogforsk, 2012).

Onboard technology can improve operative planning and execution of transport, by increasing the proportion of return loads, providing more accurate information about landings, and helping the driver make fewer incorrect choices.

Modern technology also affords new opportunities. For example, a loader manufacturer has recently shown an example of how loading in the forest, from the cab instead of from on the loader, using virtual reality technology could reduce both the occupational risks and time required to load a truck. Sensor technology, Internet of Things, and fleet management systems, collecting enormous amounts of data, are techniques that will be valuable in the work to improve transport.

In addition to all the applications relating to the truck itself, information about driving times and fuel consumption in different road sections, road geometry input to databases, and changes in road quality over time will be important. Other examples are systems that can minimize fuel consumption and trip time by using information about driving patterns in street networks, or using information about the upcoming topography, curvature, stop lights, etc. to steer a predictive cruise control (Hellström, 2007; Ericsson *et al.*, 2006).

5 Finding the best route

In Sweden, every year more than two million forestry transports take place, 200,000 new landings are visited and over 400,000 unique routes to the recipient points are generated. As the remuneration to the haulier is based on transport distance and payload, a key issue is how to correctly calculate the number of kilometres driven. Establishing an exact distance is also important for various kinds of transport planning.

Historically, transport distance has been determined in various ways:

- via points, where the landing in the forest is measured to a certain via point, from where distances to all destinations are known;
- the road district system, where the geography is divided into districts, where the distance from the centre of each district to the destinations is known;
- the LKF system, which is similar to the road district system, but is based on another administrative unit, the parish;
- based on the odometer readings by the driver.

These systems varied in accuracy as some of them, for example the district and LKF systems, based the distance from a certain point within a given geographical area, not necessary from the landing.

Different forest companies, and even different management regions within the same forest companies, have used different systems, which caused problems for hauliers working for different companies or in different regions. The established distance did not always reflect the actual distance travelled; for example, the districts used in the LKF system became larger through mergers.

Consequently, the forestry sector needed a new system. The system developed was called Calibrated Route Finder (CRF), or *Krönt Vägval* in Swedish. CRF is owned and managed by SDC, the common information hub for the Swedish forest industry, and Skogforsk has been an important partner in the development from the start.

The objective of the CRF was to create a system that is objective, transparent, fair, and that would be common for all parties in the forestry sector in Sweden. Objectivity would be ensured by using data from NVDB, the national road database, and transparency by involving all parties in the development. The system was to choose the most efficient route, but how could this be computed?

The shortest or the fastest path between two pairs of nodes in a network can be computed simply by using, for example, a Dijkstra algorithm for a minimum cost (MC) calculation (Flisberg *et al.*, 2012). Cost, as in 'minimum cost' or 'cost-based', should in this context not be mistaken for transport cost expressed in monetary units. Resistance will, where possible, be used as a synonym, describing the unwillingness to use a certain arc. For each of the 4.43 million arcs in the NVDB network, many road features are described, and the weight of their individual attribute value can be considered as a 'resistance'. In the case of the shortest path, 'distance' can be used as a resistance, and the Dijkstra algorithm would combine the arcs that provides the lowest sum of resistance, i.e. the shortest distance. The same procedure would apply if the fastest route was to be selected, but instead the resistance would be based on the calculated time it would take to travel each arc.

Skogforsk began evaluating routing based on shortest-path, cost-based routing, and routing where actual routing was reflected. The latter was chosen by the forestry sector because shortest-path or cost-based routing was often not the preferred route for either the haulier or the forest company. However, in routing, many objectives need to be considered, and reflecting the desired routes by manually applied weights for different road features soon proved to be very complicated, so another methodology was needed.

One methodology used to handle multiple conflicting objectives in decision making, in for example forest planning, is Multi-Criteria Decision Analysis, MCDA (Montibeller & Franco, 2010; Nordström *et al.*, 2010). According to Belton, MCDA is a process that seeks to *(i)* integrate objective measurement with value judgement and *(ii)* make explicit and manage subjectivity (Belton & Stewart, 2002). This methodology makes it possible to balance conflicting objectives.

A standard approach within MCDA is the Analytic Hierarchy Process, which is based on a process where a number of experts provide a relative priority between all possible pairwise combinations of objectives (Lundström *et al.*, 2014; Saaty, 1990). From these relative priorities, weights for all objectives can be calculated. However, the number of possible pairwise combinations increases rapidly when the number of objectives increase. The relationship is $n(n-1)/2$, which means that if there are 3 or 8 objectives, there are 3 or 21 combinations to prioritise. In our case, with more than 100 attributes, this means over 5000 combinations to handle in such a process, and it also includes many pairwise comparisons that would be impossible to determine, even for experts. Moreover, our case consists of both measurable quantitative factors (e.g. distance, costs, time and fuel consumption) and qualitative factors that cannot be quantified and measured (e.g. road safety and work environment). To include these considerations, we developed a methodology that involved the users, the forest companies and the hauliers, in defining best practice as the basis for the weight setting.

The first step in the new methodology was to collect detailed information about a large set of routes that both the forestry companies and the hauliers agreed were efficient. These were called 'key routes', and they describe the best-practice routes between landing and recipient point. These key routes were agreed between forest companies and hauliers. The number and the quality of these routes has been developed over time, and there are now 1500 such routes, evenly distributed over Sweden. The road features and attributes on the arcs where the key routes are drawn can be found in SNVDB. The key routes not only describe explicit quantitative factors such as arc length, road class, or whether the arc is paved or gravel, but also imply, through the presence or absence of routes, several qualitative factors such as road safety and work environment (Figure 1). In the second step, both quantitative and qualitative factors are considered, balanced and combined using the key routes.

The second step is to allocate weights to a predetermined set of road features and their attributes. These weights are then combined into one accumulated sum of weights for each arc that would then be the basis of the Dijkstra algorithm to find the minimum-cost (MC) route in the network defined through SNVDB. Here the key routes are valuable, as they represent the 'solution', i.e. the desired routing. By defining an inverse optimization problem where the key routes are the solution, the optimization process will result in such weights for each attribute value for all used road features that, when CRF is used on the nodes defining the start and endpoint of the key routes, the key routes will be generated (if possible). This is an iterative process, where the inverse optimization process stops when a minimized set of convergence criteria is satisfied. In each iteration, a number of new variables and new constraints are generated. This can be viewed as a column and row generation process. The original goal was to maximize the number of key routes found as optimal in the minimum cost route problems, but this has since changed to minimizing the deviation in total ‘cost’ between key routes and the best generated routes. The process is terminated when no more alternative routes in the minimum-cost route generation can be found.

The set of weights is now ready to be used, and the next step is to establish a single weight on arc level by adding all weights relating to the road attributes for the single arc, and multiply the total by the length of that arc. Both the quantitative and qualitative factors, expressed in the form of key routes, are now combined into one single weight that the minimum-cost (MC) procedure can use to find the best route. The system is now ready for operational routing.

When the system is called, and the coordinates of the start and end points are delivered to the system, CRF combines all the arcs that produce the minimum-cost route. However, the coordinate is often located on an arc between two nodes. In these cases, the system creates a temporary node, and calculates the distance from that node to the subsequent node. Where a coordinate is beside an arc or a node, a snapping function creates a temporary node on the nearest arc, at the position that is closest to the coordinate. In practical operation, CRF generates the distance between a coordinate defined by the forest company, and the coordinate of the measurement station near the recipient point. The extra distance driven between that position and the unloading point, plus the distance driven in the forest to find a suitable turning point for the truck, is added to the CRF distance, and forms the basis for invoicing.

CRF has been continuously developed and tested on a number of cases since 2008 (Flisberg *et al.*, 2012). There are many road features to consider, and each individual road feature can be divided into several attribute values. The road features and the number of attributes has increased since the start in 2009 (Lidén *et al.*, 2009), and the ones used in the current version of CRF, KV 4.0, are shown in Table 7.

Table 7: *Summary of road features and attributes used in the current version of CRF, KV4.0. Since the start in 2009, features 8-10 have been added.*

Id	Feature	Attributes	Comments
1	Bearing Class	4	Bearing capacity of road (truck GVW)
2	Terrain Class	5	Availability of different truck combinations
3	Functional Road Class	10	Classification of road significance
4	Maximum Speed	13	Speed limit
5	Road Width	16	Width, divided into 0.5-metre intervals
6	Road Owner	3	Government, municipality or private
7	Timber Route	2	Special forest roads
8	Passing Route	3	Special route in cities through/around city centre
9	Curvature	20	Average curvature, 10 intervals applied on road class 4-6 and 7-9
10	Hilliness	20	Average hilliness, 20 intervals applied on road class 3-6

Figure 8 shows an example of the difference between CRF and alternative objectives for route generation. In this case, the shortest path (black) and the fastest path (blue) are both shorter (19-20%) and faster (14-16%) than CRF. The route generated by CRF (green) is suggested because it uses roads of higher road class, that are not as narrow, are paved and have less curvature and hilliness. This reduces the total number of resistance points for the CRF route by 29-38%, compared to the other alternatives. The route generated by a commercial system is similar in length and time, but has a higher total number of resistance points compared to CRF (6%), mainly explained by using lower class roads. Important to remember is that, compared with other systems, CRF considers many more features that in other situations will increase the difference in resistance points.

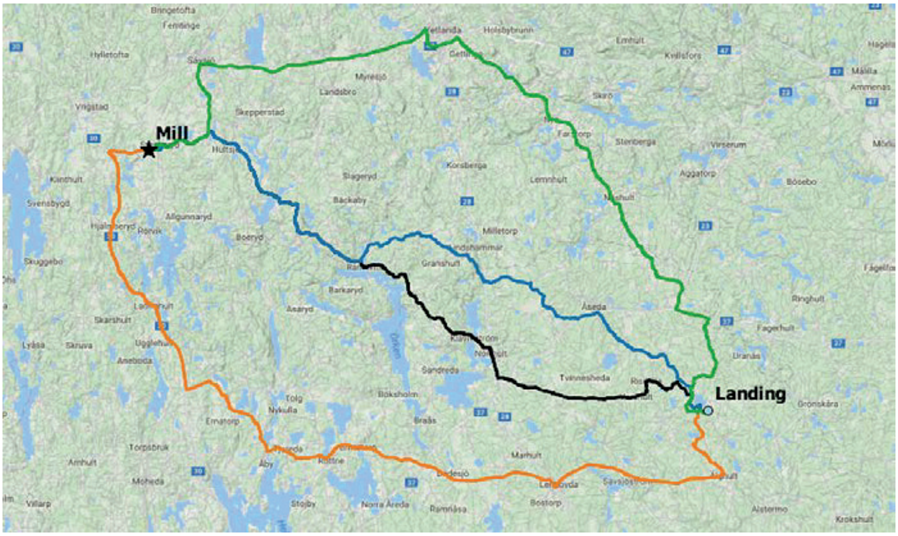

Figure 8: Illustration of different approaches to route generation: shortest (black), fastest (blue), a commercial system (orange), and CRF (green).

The number and quality of key routes have increased over time. Each setting of weights is evaluated against the key routes, and the development can be assessed in the number of key routes generated by the different versions of CRF. This development is shown in Figure 9. The distance of all the 1500 key routes is normalized to 1, and the generated distance is sorted from shortest to the left, and the longest to the right. For all versions of CRF, most routes generated are identical with the key routes, and each new version of CRF reduces the number of routes generated that are shorter and longer, as shown by the 'tails' to the left and right. The figure also displays shortest and fastest routes, and the unwillingness to use them is clear. The major difference between the CRF routes and the shortest or fastest route is that the latter typically contain a higher proportion of roads of lower functional road class, roads that are narrow and more often have gravel surfacing.

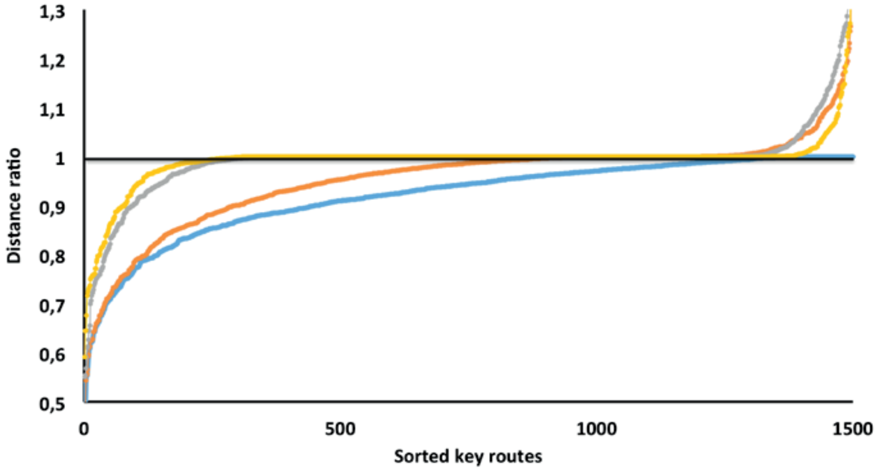

Figure 9. Comparison of the relationship in distance ratio between 1500 normalized key routes (black horizontal line) along the *x* axis, and weight settings of CRF 2009 (grey line) and 2015 (yellow line), compared to shortest path (blue line) and fastest path (orange line).

In 2009 and 2010, prototypes were tested on a limited number of forest companies, and in 2010, the first version for practical implementation was launched. Distances between the harvesting area and receiving industry could now be generated automatically, a prerequisite for a fully automated remuneration process.

Since the launch, the number of affiliated forest companies, and therefore the number of invoiced distances established by CRF, has increased. In 2016, 50% of the distances used for remuneration were established by CRF. However, we know this number underestimates reality, because the system at SDC does not register cases where a distance established by CRF is altered by the users, which is quite common for example when distance to turning point is added manually. Furthermore, most of the regular transports, for example transport of chips from saw mills to paper mills, are based on already established distances, where there is no need to generate a new distance using CRF. The evolution of the system, and when different forest companies joined the system, is shown in Figure 10.

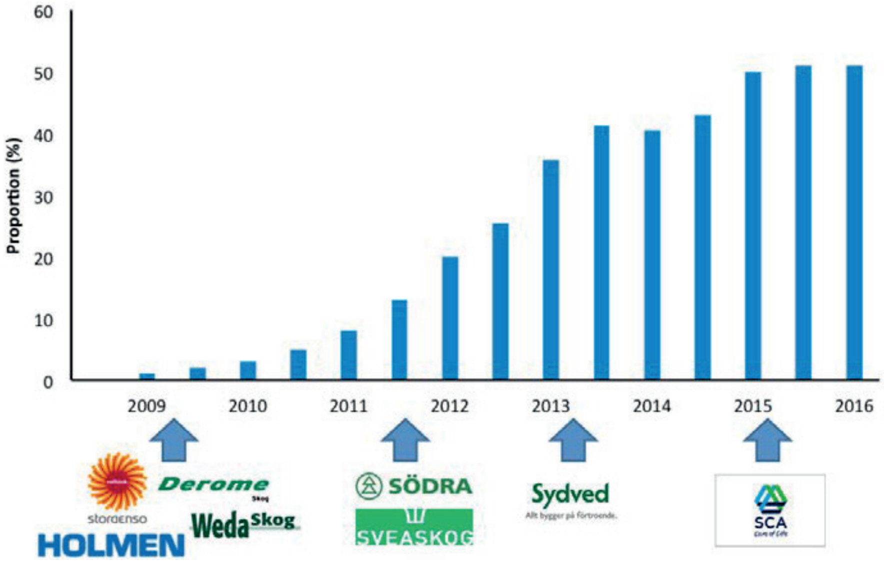

Figure 10. The proportion of invoiced distances established by CRF since the launch of the system in 2009, and when different forest companies joined the system.

One important prerequisite for efficient operation of CRF is accurate and complete data in NVDB and SNVDB, and a special organization has been set up to maintain the databases. Since CRF was introduced, the system has undergone continuous review and has been improved through reported deviations.

6 The studies

6.1 Papers I-III: Curvature and hilliness features

6.1.1 Introduction

Many deviation reports pointed out that CRF chose routes with a high degree of vertical and horizontal curvature. Drivers perceived that these routes resulted in increased fuel consumption (litres/100 km) and lower operating speed (m/s) compared to longer routes with less curvature.

The impact of road characteristics on fuel consumption and operating speed is an area that has been the subject of extensive research over many years. Important factors affecting both fuel consumption and speed are gradient (Anderson & Sessions, 1991; Peiyu & O´Reilly, 1987b; Zaniewski *et al.*, 1979; Byrne *et al.*, 1960), curvature (Donnell *et al.*, 2001; Feng & Douglas, 1993; Leisch & Leisch, 1977; Bohm *et al.*, 1965) and surface roughness (Sumitsawan *et al.*, 2009; Taylor *et al.*, 2002; McCormack, 1990; Peiyu & O´Reilly, 1987a). Sight distance and road width are also reported as affecting speed (Harwood *et al.*, 2003; Bennett & Greenwood, 2001; Jackson *et al.*, 1987; Ou *et al.*, 1983).

Earlier studies give a general insight into the effects of gradient, curvature, road surface roughness and vehicle weight on fuel consumption and operating speed for trucks, but there have been few studies of these factors for conventional logging trucks (GVW 60 tons) under typical Swedish road conditions (Figure 11). Consequently, detailed fuel consumption and speed models for planning and cost modelling are lacking. Given the wide range of road conditions for logging trucks, higher resolution studies are needed to quantify the effect of the transport environment on fuel consumption and operating speed, specifically road characteristics relating to geometry and road surface roughness.

Figure 11. A typical self-loading logging truck and trailer combination under Swedish conditions is up to 24 metres long, and has a GVW of 60 tonnes (64 tonnes from June 2015). Copyright © 2016 Taylor & Francis.

Development and implementation of models for fuel consumption and operating speed requires access to detailed and accurate data about the road network. Some earlier studies have classified road network conditions according to quality parameters, for example, alignment and surface roughness (Holzleitner *et al.*, 2013; Han, 2011; Forsberg, 2002).

A generic model should ideally be based on complete, objective, detailed and easily accessed data. In the Swedish case, this is facilitated by the National Road Database, NVDB. Data quality in NVDB suffers from shortcomings regarding completeness and accuracy due to different data sources and methodologies during data retrieval. For example, the accuracy of the z-coordinate might not vary much between positions over a road section that was measured at the same time, but when this set of coordinates must be combined into one z-coordinate at an intersection, with another set measured at another time, the relative level might differ, implying a steep slope before or after the crossing.

Until now, the objective function value for the inverse optimization problem has been to establish as many key routes as possible. This value has proved sensitive in terms of weight setting, and weights can vary considerably between similar solutions. This may present a learning problem, since the weights are available for the end users of the system. Another problem with the current objective function value is that the difference in length between some of the key routes and the routes generated by CRF becomes excessive. This difference must be reduced.

6.1.2 Objectives

The aims of these studies were to: *(i)* quantify the relative impact of road geometry, surface roughness and truck weight on fuel consumption and operating speeds for a 60-tonne Swedish logging truck, and to propose models that can be implemented in practice, based on easily accessible data; *(ii)* develop a method, based on NVDB data, to calculate and assign weights for vertical and horizontal curvature, and evaluate the result on both a detailed data set and with regard to its impact on a full national transport data set; *(iii)* propose a methodology to reduce and correct errors in NVDB for practical use, and make recommendations on how data quality can be improved by using multiple data sources; and *(iv)* evaluate a new objective function value for the inverse optimization problem that has been proposed to replace the current objective function.

6.1.3 Material and methods

Vertical and horizontal curvature is not described explicitly in NVDB, so data from multiple geographical sources must be combined with fuel consumption and speed models to compute values that reflect the perceived increase in fuel consumption and operating speed.

Studies of fuel consumption and operating speed

To cover the variation in road conditions, as well as the combinations of these, a region in southwest Sweden was identified that offered the desired variation. Selected road segments, comprising both public and private roads, were linked to form a 320-km test track that could be driven during one day by a single operator. The test track was driven empty, half-loaded and fully-loaded (corresponding to gross vehicle weights (Wt) of approximately 23, 43 and 60 tonnes) under wet autumn and dry summer conditions, in November 2010 and July 2011.

The dependent variables studied were fuel consumption (Fc) and speed (Sp), and the independent variables were gradient (Gr), curvature (Cu), surface roughness (Rsr) and truck weight (Wt), Table 8. Gradient was expressed as a percentage, and curvature (m^{-1}) was scaled by dividing 1000 by the curve radius in metres, the same definition used by Cenek (Cenek *et al.*, 2011). IRI, International Road Index, was chosen to describe road surface roughness. IRI (mm/m) is obtained through a quarter-car vehicle mathematical model applied on measured longitudinal road profiles (Sayers & Karamihas, 1998). Functional road class (Rc) was also used as independent variable, and is available from NVDB (Swedish Road Administration, 2008).

A new independent variable was introduced, integrated gradient (Ig). While gradient describes the average change in elevation over a whole road section between its start and end points, integrated gradient describes the extra vertical work involved in driving an undulating section. Integrated gradient, also expressed as a percentage, represented the sum of extra elevation gain required to overcome all ascents and descents that are not already measured by gradient (Figure 12).

Table 8. *Dependent and independent variable names, units and abbreviations.*

Variables	Unit	Abbreviation
Dependent		
Fuel consumption	ml	Fc
Speed	m/s	Sp
Independent		
Gradient	%	Gr
Integrated gradient	%	Ig
Curvature	m^{-1}	Cu
Surface roughness, IRI	mm/m	Rsr
Truck weight	t	Wt
Functional road class		Rc

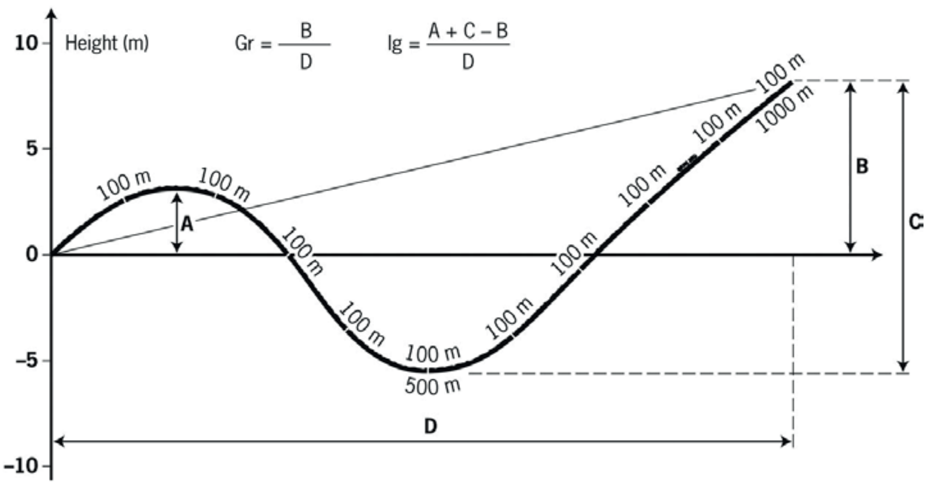

Figure 12. Principal graphical presentation of how the total data set was cut into road sections of different length and how the variables gradient (Gr) and integrated gradient (Ig) were measured. Copyright © 2016 Taylor & Francis.

The dependent variables fuel consumption (Fc) and speed (Sp) were measured with a device mounted in the truck that reads and interprets the CAN-bus (Controller Area Network) communication at a rate of 10 Hz. The independent variables road geometry and surface roughness were recorded and presented at a frequency of one observation per metre by a Vectura P45 Profilograph; a high speed profilometer, a vehicle equipped with lasers, inertial sensors and GPS (Ahlin *et al.*, 2004).

The collected data from the truck's CAN bus and the profilograph was merged using their respective GPS positioning. This was done on a metre-by-metre basis, using the Spatial Join function in ArcMap10 (ESRI, 2011). The merged data was then cut into different section lengths (100, 500, 1000, 2000 and 5000 metres) to yield data sets of varying resolution and numbers of observations (Figure 12). The statistical analysis included three pre-processing steps before regression modelling:

1. Pearson correlation test to examine the linear correlation between all the studied variables (Egghe & Leydesdorff, 2009).
2. Principal components analysis (PCA) to investigate the structure of relationships between variables and possibly reduce the multidimensionality (Jolliffe, 2002).
3. Variance inflation factor (VIF) analysis to ensure that collinearity between the chosen regression model variables does not exceed acceptable limits for use in the same regression model (Chatterjee & Hadi, 2013).

Regression analysis was then used to quantify the effect of the chosen independent variables on truck fuel consumption and operating speed (Chatterjee & Hadi, 2013). The regression models also made it possible to examine the effect of section length on statistical prediction performance. All statistical analyses were performed in the R statistical program (R Development Core Team, 2014).

Assigning weights to vertical and horizontal curvature

The x, y and z coordinates in NVDB were used to describe the position of the road in three dimensions. The x and y coordinates can be used to derive a radius, describing horizontal curvature, and the z coordinates can be used to derive a slope, describing vertical curvature. In the following section, it is important to remember that the ambition is not to exactly describe the impact of either vertical or horizontal curvature on fuel consumption or operating speed. The objective is rather to establish a relationship between different severities to obtain a fair measure. Each road attribute for curvature and hilliness will be given an accurate weight through the weight setting process, where the key routes are used as the optimal solution in an inverse optimization process.

To establish values that describe the impact of vertical curvature, the results from the European models HeavyRoute (Ihs *et al.*, 2008) and Artemis (André *et al.*, 2009), together with results from these studies, were used (Figure 13). Twenty intervals were chosen to define the attributes, seven for downward slopes, one for flat roads, and 12 for upward slopes.

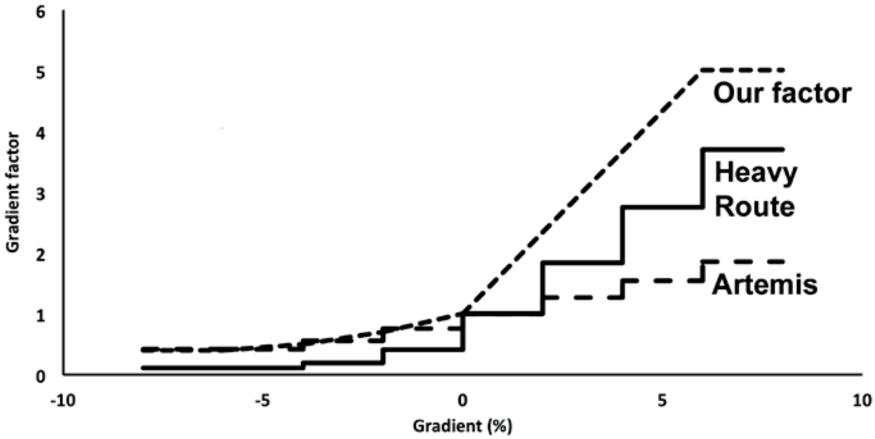

Figure 13. The HeavyRoute and Artemis models use stepwise values for different gradients, whereas the model used in this study uses a continuous scale. *x* and *y* axes represent gradient (%) and gradient factor respectively.

When establishing attributes for horizontal curvature, the variation in operating speed between a curved and straight road was computed. The first task was to calculate the radius of each curve. This was done by computing the radius at each coordinate by comparing its position to the two adjacent coordinates. The second task was to calculate maximum speed in each curve. For this, a formula developed by the Swedish Road Administration was used. The third task was to calculate operating speed over each road section, incorporating necessary braking and accelerating due to curves. Finally, this speed was compared to the anticipated speed if the road section had been straight. From the results, ten intervals defining the road attribute curvature were determined. When the attributes describing vertical and horizontal curvature had been determined, a new weight setting was done using the key routes as an optimal solution in an inverse optimization process.

Previous experience had shown that data quality in NVDB is sometimes too poor for this approach. This is particularly true for curve approximation, where small errors in positioning of individual coordinates close to each other can indicate that a curve is sharper than it is in reality. When calculating horizontal and vertical curvature, the data was filtered to reduce these errors. In addition, the method of using detailed data from a LIDAR (Light detection and ranging) survey, and spline functions that smoothen the coordinate sequence to locally remove any introduced errors and to improve road data accuracy, was tested and compared to filtering.

Another aim of this study was to investigate the effects of a change in selection of objective function value for the inverse optimization process. In the earlier version, the objective was to establish as many key routes as possible, whereas the new objective was to minimize the deviation in total 'cost' between key routes and generated routes. The main difference between the two objectives is that the new solution is less sensitive in terms of weight setting. Previously, the weights could vary considerably between similar solutions but, with the new objective, similar solutions had similar weight settings.

Three relevant reference materials were used to evaluate the effect of the methods described above: *(i)* In the analysis of the improvement in routing after attributes describing horizontal and vertical curvature had been included, 64 deviation reports related to these problems were used, together with another 63 routes in a problematic area identified by a forest company in southern Sweden. *(ii)* In the analysis of the impact of large-scale implementation of vertical and horizontal curvature on transport distances and transport work, 2.4 million transports done in Sweden under 2012 were used. This material comprised transports from 147,000 harvest areas to about 1000 recipient points using 462,000 unique routes. *(iii)* In the analysis of possible ways to improve data quality in NVDB, 90 accurately measured road sections from this study were selected. This data was compared to original and filtered data from NVDB and LIDAR data.

6.1.4 Results

Methodology to assign weights for vertical and horizontal curvature

When testing the new weight settings for road attributes describing horizontal and vertical curvature, CRF followed or changed the route in a positive way in 40% of the 64 deviation reports related to these problems. In 28 of the 63 routes in the problematic area of southern Sweden, the forest company chose the routes generated by a weight setting that included the attributes for vertical and horizontal curvature. On a large scale, using one-year data from 2012, changing the objective function reduced both transport distance and fuel consumption by 0.76-1.5%. The introduction of attributes for horizontal and vertical curvature increased transport distance and fuel consumption by 0.37-0.94%.

After several analyses and discussions of results, in October 2013 a decision was made for full implementation, and a new weight setting version was fully introduced on 17 August 2014.

Improvement of data quality in NVDB

Data on vertical and horizontal curvature from studies of the 90 selected road sections showed that estimation of average vertical and horizontal curvature did not differ much between the NVDB and LIDAR methods, with or without filtering. However, the quadratic error was high for NVDB data, especially for estimation of vertical curvature. Filtering reduced this error by 28-52% for horizontal and vertical curvature respectively. LIDAR data reduced the quadratic error for the vertical curvature data and applying splines reduced the error even further. In contrast, LIDAR data produced a very high quadratic error for horizontal curvature data, but using splines produced very good results and the error was reduced to a level far below filtered NVDB data. All data was related to data from the Vectura P45 Profilograph, which formed the basis for all comparisons.

Impact of road characteristics on fuel consumption and operating speed

Average fuel consumption in the study was 71.4 litres/100 km, and average speed 14.6 m/s. Fuel consumption and speed were affected by increased gross vehicle weight, +86% and -13% respectively (Table 9). Differences in both fuel consumption and speed were observed between the wet autumn and dry summer studies, but the following analysis made no distinction between these.

Table 9. *Average fuel consumption (litres/100 km) and speed (m/s) for different gross vehicle weights (tonnes) during the study.*

GVW (t)	Average	
	Fc	Sp
23	48.8	15.5
43	74.5	14.8
60	90.8	13.5
All weights	71.4	14.6

The range in both speed (Sp) and the independent variables varied with the length of the road sections into which the test track was divided (Table 10). The longer the road section, the smaller the range. A 1000-metre road section length was used for the following statistical analysis.

Table 10. *Average values and ranges for dependent variables; fuel consumption (Fc, litres/100 km) and speed (Sp, m/s) and independent variables; gradient (Gr, %), integrated gradient (Ig, %), curvature (Cu, m^{-1}) and surface roughness (Rsr, mm/m) by road section length.*

Variable	Ave-rage	Road section length (m)				
		100	500	1000	2000	5000
Fc	71.4	0 – 1040.0	0 – 558.1	0 – 476.3	7.2 – 388.2	19.7 – 212.4
Sp	14.6	1.4 – 27.0	2.7 – 25.6	3.9 – 25.2	4.5 – 25.0	6.5 – 23.5
Gr	0.1	–15.2 – 14.7	–8.9 – 8.7	–7.8 – 7.8	–5.7 – 5.8	–2.2 – 2.5
Ig	0.7	0 – 6.2	0 – 3.2	0 – 2.9	0 – 3.2	0.2 – 2.6
Cu	2.9	0 – 31.5	0 – 16.0	0 – 11.7	0.1 – 9.0	0.2 – 6.8
Rsr	3.9	0.6 – 34.2	0.8 – 21.2	0.9 – 17.3	1.0 – 14.9	1.1 – 11.8

Average fuel consumption increased by 107% from road classes 1-5 to 9 and speed decreased by 46%. Public roads are typically classes 1-6, and private roads are classes 7-9. The lowest values for speed and the highest values for fuel consumption, curvature and surface roughness were registered on the private roads, particularly forest truck roads (road classes 8-9). Values for gradient and integrated gradient did not exhibit a clear trend with regard to road class (Table 11).

Table 11. *Average values for dependent variables; fuel consumption (Fc) and speed (Sp) and independent variables; gradient (Gr), integrated gradient (Ig), curvature (Cu) and surface roughness (Rsr) by functional road class (Rc).*

Rc	Fc (litres/100 km)	Sp (m/s)	Gr (%)	Ig (%)	Cu (m^{-1})	Rsr (mm/m)	No. obs.
1-5	62.6	16.4	0.1	0.6	2.6	2.8	1116
7	73.6	11.3	– 0.2	1.2	2.8	6.4	109
8	80.7	12.3	0.1	0.9	3.0	5.2	369
9	129.8	8.8	0.4	0.6	4.9	7.5	100

A Pearson correlation test showed that fuel consumption was primarily correlated to gradient (Gr) but also to curvature (Cu) and surface roughness (Rsr). Speed was primarily correlated to surface roughness (Rsr) and curvature (Cu) but also to integrated gradient (Ig). Fuel consumption and speed were also correlated to each other and both were correlated to functional road class (Rc). A PCA analysis strengthened the correlation between the variables, and a VIF analysis proved that all variables could be used in the following proposed regression models.

Proposed complete regression models for driving speed and fuel consumption

Two complete regression models describing the impact of the dependent variables on fuel consumption and speed were proposed:

$$Fc = 25.1074 + Wt(0.1470) + Wt(0.1828Ig + 0.06556Cu + 0.09287Rsr) + Wt \times Gr(0.2220 + 0.3613Up), \quad (1)$$

$$Sp = 13.5733 + 26.6632 \times CuInv - 1.8624 \times RsrCuInv - 1.0773 \times Sl - 0.2299 \times Rsr - 0.0460 \times Wt - 0.5439 \times Ig - 0.0088 \times Wt \times Gr + 0.7181 \times Sl \times Gr \times Down \quad (2)$$

where:

Fc is fuel consumption (litres/100 km)
Sp is speed (m/s)
Wt is the vehicle weight (t)
Ig is integrated gradient (%)
Cu is curvature (1000/radius, m^{-1})
Rsr is surface roughness (mm/m)
Gr is gradient (%)
Up is binary (if Gr ≥ 0, then Up = 1, else Up = 0)
CuInv is the inverse of Cu plus the constant 2 $(Cu+2)^{-1}$
RsrCuInv is Rsr (mm/m) divided by curvature plus the constant 2 $(Rsr*(Cu+2)^{-1})$
Sl is binary (single lane=0 on public roads, 1 on private roads)
Down is binary (if Gr ≥ 0, then Down = 0, else Down = 1).

The models explained 84% (Equation 1) and 80% (Equation 2) of the variation in fuel consumption and speed respectively, and all the presented variables were significant ($p < 0.001$).

Comparison of parameter estimates by section length

Given that the test track of 320 km could be partitioned into varying section lengths prior to regression analysis, thereby creating different data sets, parameter estimates could be compared between varying resolutions. The coefficient of determination (R^2) for the proposed models increased with road section length, from 61-65% for 100-metre sections (Equation 1) up to 85-87% for 5000-metre sections (Equation 2). Parameter estimates and variable significance also varied with section length. A section length of 1000 metres yielded both a high coefficient of determination and significant effects of all the included variables.

Application example of the models

The proposed regression models were used to simulate fuel consumption and speed of two haulage assignments of low and high difficulty with assumed values for curvature (Cu), surface roughness (Rsr) and integrated gradient (Ig) (Table 12). The difference between low- and high-difficulty conditions was reflected in the distribution of road classes and their associated characteristics. While the overall gradient from landing to mill to landing for both assignments was set to 0, the associated values for integrated gradient, curvature and surface roughness were retrieved from the corresponding upper and lower quintiles in the boxplot in Figure 6 in Paper I (Svenson & Fjeld, 2016). Each assignment involved driving 100 km unloaded and 100 km loaded. Terminal handling, i.e. self-loading at landing in the forest and measurement and supported unloading at the recipient point, was set to 60 minutes and fuel consumption to 5 litres per load in total.

The estimated turnaround time for the low-difficulty assignment was 239 minutes and for the high-difficulty assignment 327 minutes. The increase due to high-difficulty conditions was 37%.

Table 12. *A comparison of simulated turnaround time consumption (min/load) for the complete and simplified models for haulage assignment of 100 km one way, on high and low difficulty conditions defined by different road class (Rc), integrated gradient (Ig, %), curvature (Cu, m^{-1}) and surface roughness (Rsr, mm/m).*

						Fuel consumption (litres)/Time (min) according to complete model			
Difficulty	Distance (km)	Rc	Ig	Cu	Rsr	Driving loaded	Driving unloaded	Terminal handling	Round trip
Low	100	1-5	0.3	1	2	52 / 94	34 / 85	5 / 60	92 / 239
High	35	7-9	1.3	4	7	86 / 142	45 / 124	5 / 60	136 / 327
	65	1-5	0.9	4	3				

Proposed simplified regression model for driving speed and fuel consumption

The proposed complete models (Equations 1 and 2) assume that numerous variables for describing road characteristics are available. While gradient (Gr), integrated gradient (Ig) and curvature (Cu) can be derived from NVDB using the road geometry coordinates, road surface roughness (Rsr) is not a measure available in practice. Simplified models were therefore tested (Equations 3 and 4) where the effects of surface roughness are assumed to be partially represented by road surface type (Rst, paved or gravel) in Equation 3 and the variable single lane (Sl, public or private roads) in Equation 4:

$$Fc = 24.4455 + Wt(0.2377 + 0.2587Ig + 0.08389Cu + 0.2450Rst) + Wt \times Gr(0.1882 + 0.4480Up), \quad (3)$$

$$Sp = 11.4205 + 26.8552 \times CuInv - 3.2396 \times Sl - 0.0489 \times Wt \quad (4)$$

where:

Fc is fuel consumption (litres/100 km)
Sp is speed (m/s)
Wt is the vehicle weight (t)
Ig is integrated gradient (%)
Cu is curvature (1000/radius, m^{-1})
Rst is binary (if road surface is paved, then Rst = 0, if road surface type is gravel, then Rst = 1)
Gr is gradient (%)
Up is binary (if Gr ≥ 0, then Up = 1, else Up = 0)
CuInv is the inverse of Cu plus the constant 2 $(Cu+2)^{-1}$
RsrCuInv is Rsr (mm/m) divided by curvature plus the constant 2 $(Rsr*(Cu+2)^{-1})$
Sl is binary (if public road, then Sl = 0, if private road, then Sl = 1).

The simplified models explained 82% (Equation 3) and 72% (Equation 4) of the variation in fuel consumption speed respectively, and all the presented variables were significant ($p < 0.001$).

6.2 Paper IV: Development of an augmented road data network

6.2.1 Introduction

In NVDB, all roads are defined through reference segments that are described in geographical and topographical detail, with many road features and their associated attributes. There are 2.3 million reference segments, with an average length of 258 metres and an average of 13 geometric coordinates, i.e. one set of geometric coordinates for each 20 metres. The reference segments generally represent two arcs (each direction of a road) in the network, and nodes are used to connect them at intersections.

Figure 14 illustrates an example of an intersection and several reference segments. It is important to note that there is no separation, in general, between lanes and their connection in nodes. Some parts of the road network contain a natural separation of lanes. This is the case with, for example, parts of motorways and '2+1 roads' where a wire railing separates traffic travelling in opposite directions; there are either 2 or 1 lanes in each direction, alternating along the road to facilitate overtaking.

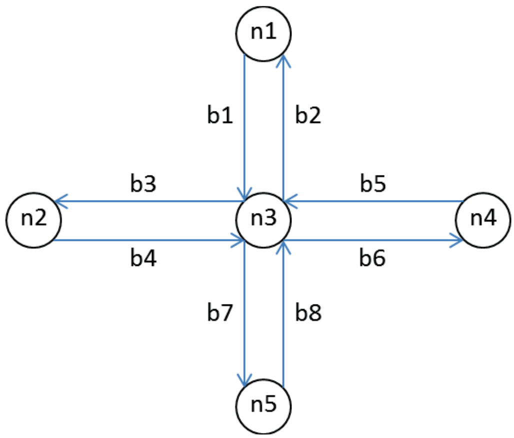

Figure 14. Representation of a standard four-way intersection in the current basic road data network. Circles represent nodes, and arrows represent arcs.

NVDB contains two features that control the possibility to turn in an intersection; one is ‘Possibility to turn’ and the other is ‘Forbidden turn’. The first feature, ‘Possibility to turn’ indicates whether different types of vehicle combinations can turn left or right in different types of intersection. Sometimes the angle between the connecting roads is too acute for a 24-metre truck and trailer combination to negotiate. This mainly occurs in junctions between lower class roads, often narrow forest roads, and roads of higher class.

Forbidden turning mainly concerns larger roads and is well defined in the NVDB. Turning left from a main road is a dangerous maneuver, and traffic regulations sometimes prohibit left turns and stipulate a small detour to the right before crossing the meeting lane. However, neither of these attributes have been implemented in CRF. One reason is that the system is mainly concerned with distances; these attributes did not receive enough attention, as they were considered to have less impact on the distance calculations. However, now that the system is being used operatively, it is critical that the correct route is given. Any error in displayed routes will reduce confidence in the quality of distance calculations. Another issue with turning is that some possibilities may be suggested that are not forbidden but may be impossible. Examples of this are illogical U-turns and other sharp, impossible turns on roads. These may occur in routes in the current version of CRF, but never in practice.

Some deviations reported by drivers are that routes recommend short-cuts on roads of low quality, but short-cuts are not perceived as an improvement to the route. One example is to be driving on a larger road and then turning off onto a smaller road, to save a few kilometres.

Another question raised is the need to also include the ‘cost’ (resistance) associated with different turning options in intersections, i.e. deceleration before, waiting in the intersection and acceleration afterwards. Intersections increase both time and fuel consumption as well as stress on the driver. With more planning and operational systems to consider, it is important to obtain correct and high-quality route times. Correct fuel consumption measurements are also particularly important in view of growing concern about environmental impact and the need to measure emissions correctly.

The problem is that the current network cannot handle any of the issues described because there is no information on the sequence of arcs. A Dijkstra’s algorithm offers several possibilities for implementing and forbidding different turning possibilities. The main alternatives are to use either the basic static network and store, for example forbidden turns, dynamically in lists outside the network, or expand the current basic network into an augmented network. In the case of the latter, a static expanded network, all turning options must be included as arcs, so the number of arcs and nodes will increase considerably. This has a negative effect on solution time, and increases demands on memory. However, when using dynamic lists in the basic network, all forbidden turns are stored in lists outside the network. This solution keeps memory usage low but will increase the solution time, as the system must search through separate lists of forbidden turns. This approach may also result in a non-optimal route.

Our solution to the above issues is to construct an augmented network. We expand the number of nodes and arcs so that travel is not possible between two given nodes in two directions and so that all turning options in a road intersection are represented by a unique arc. This considerably increases the number of nodes and arcs but, in an augmented network, forbidden turns can be identified and removed by removing arcs. Furthermore, because we are keeping track of each turn and stop, we can include specific 'costs' (or time and fuel consumption) on each arc, since we have information on required braking, stopping and acceleration. This is not possible on a standard network where we have no information about specific sequences of links or arcs.

6.2.2 Objectives

The objectives of Paper IV were to: *(i)* develop a general methodology to construct an augmented network and to evaluate whether it can effectively deal with issues related to forbidden or impossible turns; *(ii)* evaluate how an augmented network could be used to handle shortcuts from higher-quality roads into lower-quality roads; and *(iii)* develop processes to calculate accurate time and fuel consumption for trucks when braking, stopping, turning, and acceleration in intersections of different types.

6.2.3 Material and methods

Forbidden and impossible turns

There are guidelines regarding the geometric construction of junctions where forest roads are connected to other roads (Gunnarsson *et al.*, 2011). The angle between the connecting roads was calculated by using the adjacent coordinates in NVDB. If the angle is too small, it was concluded that such a turn is considered as impossible. A cut-off angle of 50 degrees was used, and all other turns were removed from the network. When there was information in NVDB on forbidden turns, the corresponding arc was removed in the augmented network.

Short-cuts on low-quality roads

In some deviation reports, truck drivers requested avoiding short-cuts on lower-quality roads, so different levels of 'costs' (resistances) were added. These 'costs' correspond to an extension of the short-cut, thus making them less attractive.

Estimation of fuel consumption and travel time in intersections

If we want to calculate the effect on intersections, we must consider time and fuel consumption associated with deceleration, stopping and acceleration in various types of intersections, as well as when travelling along roads of different quality,

To estimate fuel consumption along roads and in intersections, data from Papers I and III was used. From Paper I, a total of 90 road sections (199 km) were selected for the detailed analysis. This consists of data from detailed road measurements collected by the Vectura profilograph P45 vehicle, and fuel and speed data from a truck. From Paper III, the approach describing the effect of hilliness was used.

To estimate time consumption along roads without any curvature, we used an average speed based on the road classification and the maximum speed on the segment. For road segments with curvature, we used the model from Paper III.

If we are to include the effect of deceleration, stopping and acceleration on time consumption in different intersections in the network, we need an estimation of how these situations affect travelling time. Total time delay in an intersection includes geometric delay, queueing delay, deceleration and acceleration delay, and stopped delay (Sisiopiku & Oh, 2001). Different kinds of intersections between roads of varying functional road class, as well as the turning directions, were considered. With the information on initial speed after an intersection, we can compute the additional fuel consumption needed to accelerate to the nominal speed on the specific arc, as well as the fuel consumption caused by waiting at the intersection. This information is then used on the arcs representing each turning option.

To evaluate the impact of including different turning restrictions and time and fuel consumption in intersections, we compared the proposed approach with current transport data in Sweden from one year (2012). This data comprised 2.4 million transports from 147,000 harvest areas to about 1000 mills. This provided 462,000 unique routes, and enabled us to compare the methods in terms of average distance, time and fuel consumption.

Various case studies were defined for the result generation and analysis. The definitions of the cases and their sizes (number of nodes and arcs) are given in Table 13. The current system is based on case A0, and case A is the corresponding system in the augmented network. The basic network was expanded by introducing more nodes and arcs (Figure 15). Any route in A0 will be the same as in case A, but with more information to analyse.

Table 13. *Definitions and dimensions of the different cases.*

Case	No. of nodes (thousands)	No. of arcs (thousands)	Description of network used in each case
A0	2250	5059	Current non-augmented network
A	9240	16092	Augmented network
B	9240	16091	A + forbidden turns
C	9240	12577	C + forbidden U-turns
D_j	9240	12352	B + impossible turns (with different limits on turning angle *j*=5, 10, …, 80 degrees)
E1 (E2, E3)	9240	12352	D + 'cost' for turning onto low-quality roads (E2 = double turning 'cost', E3 = very high turning 'cost')
F1 (F2)	9240	12352	D + penalty on arc 'costs' for increased fuel consumption in intersections (F2 = double penalty 'cost')
G1 (G2)	9240	12352	D + penalty on arc 'costs' for increased fuel and time consumption in intersections (G2 = double penalty 'cost')
H1 (H2, H3)	9240	12352	G1 but with 50% of waiting time in intersections (H2 = 200%, H3 = 400%)

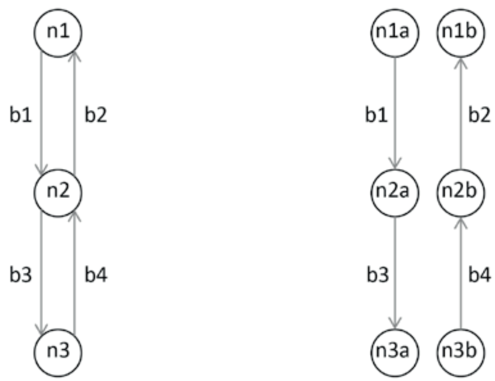

Figure 15. Principal difference between a basic network (left) and an augmented network (right). In the augmented network, an illegal U-turn is not possible because there is no connection between the sets of nodes relating to the two directions.

In the other cases, we have added some features to analyse the changes in various properties. In case B, we add the registered forbidden turn and, in C, illegal U-turns. In case D, difficult turns are added. Here, different cut-off angles are used as the limiting angle to restrict U-turns and where roads intersect at very acute angles. In cases E1-E3, we analyse the behaviour when different 'costs' are used to limit the use of lower-quality roads as a short-cut. In cases F1 and F2, we tested the effect of adding some penalties to the fuel consumptions in intersections. For cases G1 and G2, we also added 'costs' for the time for waiting at intersections. In cases H1-H3, more sets of waiting times in crossings are used.

6.2.4 Results

By expanding the basic network into an augmented network, for example a U-turn is impossible in node n2 (Figure 15). The number of new nodes and arcs increases considerably (Table 14) when an augmented network is constructed, especially in intersections (Figure 16).

Table 14. *Number of arcs and nodes for the most common intersections in a basic network compared to an augmented network.*

	Basic network		Augmented network	
	No of arcs	No of nodes	No of arcs	No of nodes
No intersection	4	3	4	6
3-way intersection	6	4	12	12
4-way intersection	8	5	20	16

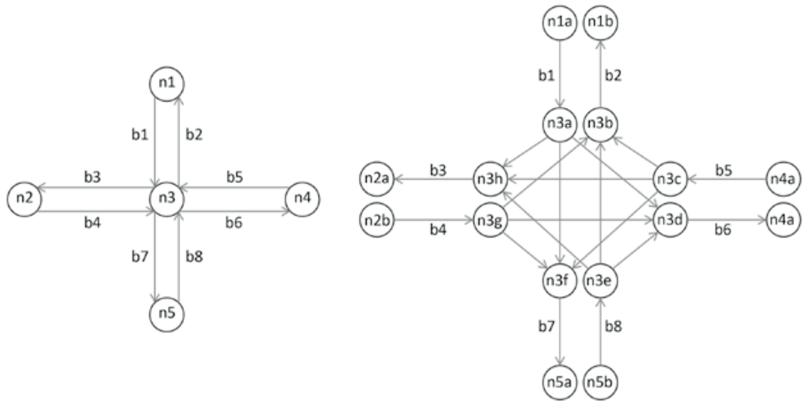

Figure 16. Principal difference between a basic network (left) and an augmented network (right) for a four-way intersection. Each turning option is modelled with an arc.

When the augmented network was constructed, the number of nodes increased from 2250 to 9240, and the number of arcs from 5059 to 16,092. When all turning restrictions (D45) were implemented by removing arcs representing forbidden or impossible turns from the network, the number of arcs decreased to 12,352. This increased the average distance of all unique logging routes in Sweden during 2012 by 40 metres (Table 15); 22,000 routes out of 462,000 became longer, and 44,000 shorter.

Adding ‘costs’ for increased time and fuel consumption when taking a short-cut on lower-quality roads (E1) or in intersections (G1) did not affect the number of nodes or arcs in the network. Both increased average distance compared to A, and for G1, time and fuel consumption was reduced. Applying ‘costs’ for turning reduced both the time and fuel spent in intersections. If the ‘cost’ related to intersections was further increased, the effect on time and fuel consumption became even larger.

Table 15. *Impact on number of nodes and arcs, average distance, time and fuel consumption, on unique logging routes during 2012, by implementing all turning restrictions (D45), avoiding short-cuts (E1) and adding extra ‘costs’ for intersections (G1), compared to an augmented network (A).*

	A	D45	E1	G1
No. nodes	9240	9240	9240	9240
No. arcs	16092	12352	12352	12352
Distance (km)	88.81	88.85	89.07	89.78
Longer routes (thousands)		22	66	183
Shorter routes (thousands)		44	54	100
Time (min)	93.6	93.7	93.7	93.2
In intersections (%)	9.4	9.3	9.2	8.1
Fuel (litres)	47.2	47.2	47.2	46.5
In intersections (%)	15.4	15.4	15.3	13.4

By increasing the ‘cost’ of leaving a better road for a short-cut on a lower quality road (the E-cases), the number of these turnings will decrease (Table 16). In the table, case D serves as the reference, and E1 and E2 two levels of ‘costs’, and the reference material is the 462,000 unique routes from 2012.

Table 16. *Difference in number of turnings per route to lower-quality road, depending on case*

Aspect/Case	D	E1	E2
Turnings from Rc 0-2 to Rc 3-6	465,418	457,701	450,130
Turnings from Rc 3-6 to Rc 7-9	376,409	322,228	316,155
Turnings from Rc 0-2 to Rc 7-9	94,028	81,677	75,040
Average distance (km)	88.85	89.13	89.07
Average fuel consumption (l)	47.2	47.3	47.2

An augmented network increases the number of nodes and arcs, memory requirement, and the solution time of finding the minimum 'cost' route from the forest to the industry increased by a factor of 3-4, Table 17. Finding the route tree for all mills took 555.66 seconds, with an average solution time of each route of 1.18 milliseconds in the basic network. In the augmented network, the corresponding time was 1748.85 seconds in total, and 3.72 milliseconds for each route. For the key routes, total solution time was 44.6 milliseconds in the basic network, and 185.5 milliseconds in the augmented network. The increase in solution time is normally not critical for single calls to the server, but it might cause problems in the case of multiple calls in conjunction with flow optimization at the strategic level.

Table 17. *An augmented road data network can handle undesirable turnings, and enables the inclusion of estimations of fuel and time consumption in intersections. Size of network and memory demands increase, and so does solution time.*

	Basic network		Augmented network
Capable to handle:	Static	Static and side information*	Static
• illegal turns	No	Limited	Yes
• illegal U-turns	No	Limited	Yes
• turning to low-quality roads	No	No	Yes
• time and fuel consumption in intersections	No	No	Yes
Size of network			
• nodes (million)	2.3	2.3	9.2
• arcs (million)	5.5	4.5	12.3
Memory requirement	Medium	Increased*	Larger
Solution time	Short	Increased	Longer (3-4 times)

* side information is kept outside network in separate tables

6.3 Paper V: CRF in a wider context

The objectives were to provide a general description of the Calibrated Route Finder (CRF) distance measurement system, including a review of the historical background, the purpose and how it has evolved since the start. The presentation includes the Operations Research challenges met, and how they were addressed. The current system in operation is also described, and its impact estimated. The actors involved are presented and the flow of information between them described.

Logging transport is paid by payload (normally tonnes) and distance travelled. Finding the best route when many conflicting objectives are involved is very difficult, and CRF was developed to create an objective and transparent system for distance measurement that could replace previous systems used by the forest companies. These could be imprecise and using different systems created problems when hauliers worked for different forest companies. Another aim was to reduce administration by automating distance establishment.

In the 1990s, the forestry sector conducted successful trials on collecting and using digital map information about, for example, road conditions. This was followed by the NVDB, the national road database jointly developed by the forestry sector, the Swedish Transport Administration, the Swedish Transport Agency, the Swedish Association of Local Authorities and Regions, and the Swedish Mapping, Cadastral and Land Registration Authority. The design of NVDB, which covered the whole road network in Sweden, formed the basis for the subsequent development of CRF, which is owned and managed by SDC, the information hub for the Swedish forest industry. Skogforsk has been involved in the development of the CRF system since the start.

In the development of CRF, key routes play an important role. Key routes, evenly distributed over the country, describe best practice in the route selection from landing to recipient points. The 1500 key routes capture both quantitative and qualitative factors, such as distance, operating speed, fuel consumption and emissions, road safety and work environment. By using inverse optimization, where the key routes act as the optimal solution, weights can be allocated on selected road features described in NVDB. At a road arc level, these weights will then form a single objective, the resistance to using a single arc. That objective is then used in a minimum-cost optimization to generate routes when CRF is used in practical operation.

The system was launched on a small scale in 2009, and full scale in 2010. Gradually, more and more companies have joined, and today all forest companies are using the system for distance measurement. It is documented that just above 50% of the distances invoiced are based on CRF, but we know that a high proportion of the other invoiced distances have used CRF as the basis for distance assessment.

An important evaluation has been to compare CRF routes against shortest paths and fastest paths, as these are often discussed as alternatives by the drivers and companies. Evaluating the qualitative improvement is difficult. Table 18 shows a qualitative assessment of CRF in comparison with shortest path and fastest path, for all transports in 2012. By definition, the shortest and fastest routes are shorter and faster than the CRF routes, but both these routes involve more time/distance on lower-quality roads, gravel roads, and narrower roads. In most cases, curvature and hilliness are also considerably greater than on the CRF routes.

Table 18. *Comparison showing improvement generated by CRF in terms of attributes reflecting road safety and stress, compared to shortest path and fastest path. Results are based on transports in 2012.*

Attribute, or aggregated attributes	CRF	Shortest path	Fastest path
Average distance, km	88.54	84.18	86.77
Road class 7-9, km	3.89	17.29	12.37
Max 30 km/h, km	0.20	0.39	0.12
Gravel surface, km	5.99	18.78	11.76
Narrow roads: 2.5-4 m width, km	1.68	4.46	2.69
Severe curvature, km	0.73	2.17	1.60
Severe hilliness, km	4.54	6.21	3.51
Approach routes, km	0.43	0.27	0.35
Passing routes, m	18.81	13.20	15.51

Deviation reports have been an important input in the development of CRF. These are submitted by the end users, for example drivers or transport managers. The reason for a deviation varies – often it concerns local conditions and data improvements in NVDB but in some cases the deviation indicates a need for improvement in CRF. For example, vertical and horizontal curvature and turning restrictions were incorporated as a result of the deviation reports.

Deviation reports are first handled by VMF, the impartial timber measurement association of Sweden, and reports not related to local conditions are sent to the CRF board, a group of company representatives who, together with the other actors, evaluate and initiate further developments (Figure 17).

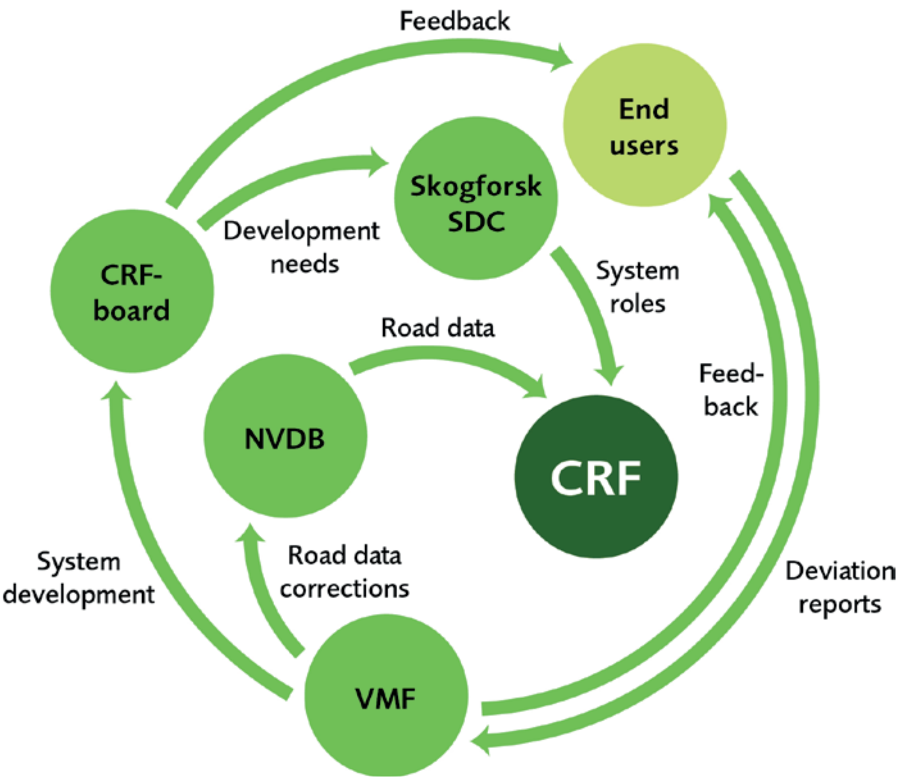

Figure 17. Illustration of the process relating to deviation reports and system development. The process begins with an end user submitting a deviation report to VMF. Illustration: Per Thorneus.

End users submit CRF deviation reports via a web interface, via the companies' own interfaces with SDC and CRF, or via a direct connection to the system. The response is in the form of a distance and a geometry describing the route. The system involves many actors (Figure 18). Besides SDC, Skogforsk and NVDB, the VMF and the CRF board are also involved in system management and development. The end users of the system are the forest and haulage companies that use the system in different situations, mainly to establish a distance for operative planning, but also for more long-term planning.

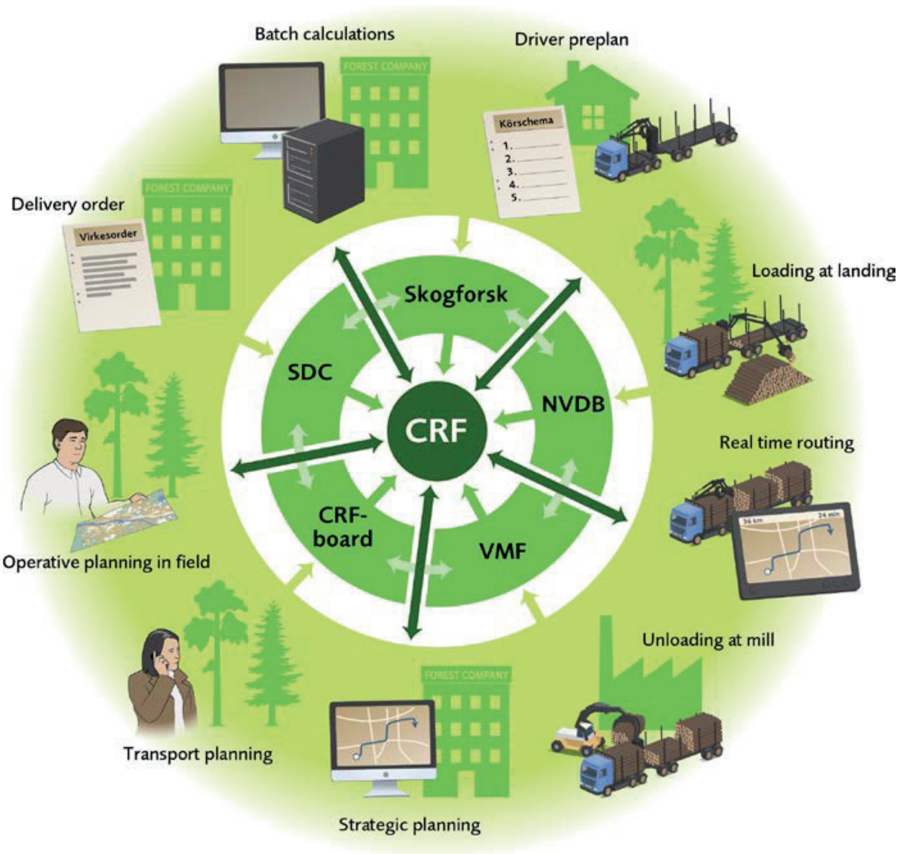

Figure 18. An overview of the CRF system – its actors and users. Illustration: Per Thorneus.

CRF is not only used for calculating distance. The geographical presentation of the route on a map that can be followed in the cab of the truck is useful for the driver. It is therefore crucial that the system avoids both illegal and impossible maneuvers, such as sharp turns. In the current version of CRF, based on a basic network, some of these situations do occur, and cause difficulty. In Paper IV we propose an expansion of the current network into an augmented network, which can handle all these possible situations. An augmented network will also allow, for example, more detailed calculations of increased fuel consumption and changes in operating speed for turnings in different directions in various intersections, and add extra weights for undesirable maneuvers.

A key feature in Swedish forestry sector accounting and information flow is the timber order. It forms the basis for the timber transaction, and the monitoring and control of the flow of timber. The timber order initiates the flow of distance and routing information relating to transport orders from the forest company to the trucking company and the subsequent invoicing process. The transport order, in turn, contains all the information needed by the driver, such as location of landings and timber assortments and their individual destinations.

An obvious question concerns the benefits and transport cost savings generated by the system. The primary purpose of CRF was to establish fair and efficient route generation, but annual administration costs are expected to be reduced by SEK 22.5-45 million, and fuel and time consumption to be reduced by SEK 45-67.5 million in Sweden. Another benefit is more efficient collaboration between the actors involved.

Development is ongoing. Examples are the inclusion of trucks with gross vehicle weights (GVW) of 74 and 90 tonnes, and using LIDAR to improve the data quality in NVDB. We also consider a completely new transport agreement, where the standard distance-based system is replaced by a quality point system. The CRF system is also being used for scenario analysis in an evaluation of the consequences of introducing a vehicle tax on public roads, and increasing GVW to 74 tonnes.

7 Discussion

These studies have shown methods that improve routing in CRF. These improvements include the development and incorporation of road features describing perceived hilliness and curvature, a detailed description of how road characteristics and truck weight impact fuel consumption and operating speed for logging trucks, and how expanding the road data network used in the CRF routing allowed the system to consider different turning situations. We now have models that enable consideration of vertical and horizontal curvature, road surface roughness, time and fuel consumption, and turns at intersections, in practical routing.

These findings have several practical implications. There are many feasible route options available to a driver from landing in forest to mill, but this type of model can help find the best routes in terms of productivity and transport costs, as well as wear on truck, road safety, working environment and greenhouse gas emissions. Wages and fuel together comprise approximately one-third of total transport cost, so this new knowledge allows accurate calculation of two-thirds of the transport cost of individual logging assignments, and the findings will provide a basis for improved transport cost models.

The models need to be validated and further developed, for example by examining fuel consumption and speed models involving more trucks and drivers, in other areas of Sweden and under different seasonal conditions, such as winter and spring thaw. These models must also be extended to ensure relevance for heavier and longer trucks, such as the 74- and 90-tonne trucks currently being tested.

The fuel consumption and speed models were developed for road sections of different lengths, using detailed data describing road characteristics. A practical use of these models, based on less detailed data from other sources, such as NVDB, requires a transformation and validation of the models. In the case of NVDB, for example the x, y and z-coordinates can be used to describe the impact of vertical and horizontal curvature on speed and fuel consumption, and further improvements of data quality in NVDB would increase the value of these models. The models describing effects on time and fuel consumption at intersections also need to be improved. Currently, estimates on stopping and turning times are set by road experts, but more sophisticated approaches are needed to identify more accurate descriptions of delays at different kinds of intersections as described in earlier studies (Sisiopiku & Oh, 2001; Kimber & Hollis, 1979; Tanner, 1962).

7.1 Vertical and horizontal curvature in CRF

Paper III proposed a method to establish weights for the road features curvature and hilliness using coordinates describing road geometry and topography in NVDB. The method involved establishing and classifying horizontal curve radii and vertical curve gradients. These were then combined with existing models (André *et al.*, 2009; Ihs *et al.*, 2008) and new empirical data from this project describing fuel consumption and speed, and weights were then assigned for these attributes through an inverse optimization process.

The new weight settings solved 40% of the deviation reports relating to routes on roads that were considered to have a high degree of either/or both curvature or hilliness. In 28 out of 63 routes where a forest company in southern Sweden had reported excessive vertical and/or horizontal curvature, this weight setting generated alternative routes that were preferred. The conclusion is that the new weight setting in CRF is successful and can provide better descriptions of routes that include a high degree of vertical and horizontal curvature.

Results from these studies were critical observations in the process to determine whether the new features should be implemented in the CRF system. A new objective function for the inverse optimization process to find weights for the road attributes was introduced in Paper III. The new function minimizes the total deviation in resistance instead of maximizing the number of key routes met using the weight setting. This, together with subsequent improvements to the key routes, was beneficial, as average distance and fuel consumption were reduced by 0.76-1.5%.

After several more analyses and discussions of results, in October 2013 a decision was taken for full implementation, and a new weight setting version, based on the new objective function incorporating vertical and horizontal curvature, became operational on 17 August 2014.

7.2 Modelling logging truck fuel consumption and operating speed

Studies I and II developed models describing the impact of road characteristics and truck GVW on fuel consumption and operating speed for a 60-tonne logging truck. Earlier studies have produced knowledge about how individual road characteristic affect fuel consumption and operating speed, but no models have incorporated the most important variables into one model that can be used for practical modelling of fuel consumption and operating speed under Swedish conditions.

The models were derived by using an experimental design delivering both high variation and precision for dependent and independent variables. Combining high-quality and high-resolution data from profilograph surface and geometry measurements and the truck CAN-bus speed measurements provided an opportunity to use the best equipment for measuring the variables. The models were derived using road data with a variation in values, covering most roads in Sweden, so the models could be applied not only in the area of the study, but on Swedish roads in general.

Gradient was found to be the key variable for fuel consumption. Visualizing the impact of gradient and truck weight on truck fuel consumption, modelled in Equation 1, had the same appearance as that modelled by ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) (EEA, 2013), Figure 19. The ARTEMIS model shown in the figure refers to an articulated 50–60-tonne Euro IV truck. The complete model is based on an integrated gradient of 0% and surface roughness of 2 mm/m. For negative gradients, a flatter slope is shown in the proposed model compared with ARTEMIS, but the flatter slope was influenced by several observations with notably higher fuel consumption. Because these were found in both autumn and summer studies, they are most likely to be associated with sections where geometry and road width required acceleration after speed reduction, for example, when passing a tight downhill curve on a private road.

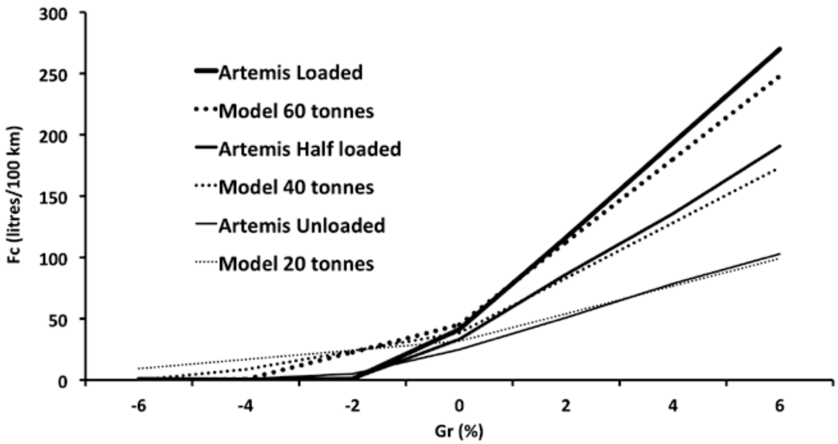

Figure 19. A comparison of fuel consumption by gradient and weights for the proposed model, Equation 1 (Ig=0 %, Cu=0 m^{-1} and Rsr=2 mm/m) and ARTEMIS model (articulated 50-60-tonne Euro IV truck, Sp=86 km/h).

The influence of gradient and weight on speed, as modelled with the complete model (Equation 2), was shown to behave differently for negative and positive gradients, depending on whether the road was public or private, expressed in the variable single lane (Sl). On positive gradients, speed decreased for both types of roads, which was also reported by Zaniewski (Zaniewski *et al.*, 1979) on paved roads.

However, on negative gradients, there was a distinct difference. On public roads, speed increased, which is a natural reaction when potential energy is transformed into operating speed, but on private roads, the opposite was seen, as speed decreased with increased negative gradients. This pattern has been reported earlier (Torset, 2011; Byrne *et al.*, 1960) and can be explained by the driver needing to maintain a lower speed on narrow and curved roads to keep the vehicle safely on the road, or to be able to brake quickly when meeting another vehicle.

Curvature was found to be the key variable for truck speed, alone and in interaction with surface roughness. In the model, a variable that inverted curvature was used to obtain an asymptotic shape, a shape that seems to be a logical response to increased curvature; the impact of curvature is greatest at high speeds, where the centrifugal forces are greatest, and the impact of speed is small at high curvature levels. The asymptotic shape of the impact of curvature on operating speed has been reported earlier (Simwanda *et al.*, 2015; Torset, 2011; Bohm *et al.*, 1965; Byrne *et al.*, 1960). Curvature also had a significant role in the fuel models.

Surface roughness also shows a similar speed reduction pattern as roughness increases. In this study, the combined effect of surface roughness (Rsr, mm/m) is 2 m/s for each change in surface roughness by 1 mm/m. This is similar to Ihs, who showed a change of 2-3 m/s per 1 mm/m (Ihs & Velin, 2002). Ou showed that an increase of 1 mm/m reduced speed by 4.5 m/second, much higher than in this study, but the initial speed in Ou's study was higher (Ou *et al.*, 1983).

In the absence of data about road width, the single lane (Sl) variable was used in the speed model to capture the impact of sight distance and road width on operating speed. Sight distance is important to avoid collisions with other vehicles, and becomes shorter as roads narrow (Bohm *et al.*, 1965; Byrne *et al.*, 1960). Sight distance is limited on much of the private network because the roads, often single lane, are often surrounded by dense forests. In contrast, public roads are normally two lanes.

The other road factor captured by the single lane (Sl) variable, road width, is also correlated to speed, because private roads might have soft shoulders that can give way if the truck/trailer comes too close. If a tire cuts down into the soft surface, there is a risk of rollover due to the high centre of gravity of a fully-loaded truck. This problem has been reported earlier (Bohm *et al.*, 1965) and has been accentuated recently since a maximum GVW of 64 tonnes is now permitted in Sweden. It is a generalization to say that all private roads are single lane roads, but provided a useful simplification at this stage when data about road width was unavailable in NVDB and was not measured in this study. In the future, the inclusion of actual road width would probably improve the model further.

The study introduced a new variable, integrated gradient (Ig), a variable that captures the vertical movement required for the truck to overcome all ascents and descents over a road section better than gradient (Gr). Integrated gradient was found to influence both fuel consumption and operating speed. In the fuel consumption model, integrated gradient, surface roughness and curvature, in interaction with weight, were found to have additional effect on fuel consumption. Here, too, the explanation is simple; the heavier the truck, the more energy is lost in curves and on rough roads, as reflected by the higher fuel consumption for functional road classes 7-9.

Speed was not used as a variable in the fuel model in this study, although it has been reported as important in other studies (Karlsson *et al.*, 2015; Woodrooffe, 2014; Børnes & Aakre, 2011). As air resistance increases by the cube of speed, the impact of air resistance on fuel consumption can be considerable, especially at higher speeds, but these speeds were uncommon in this study. The speed variable was not used in the models because speed is more a dependent than independent variable, as speed in this study resulted from, and was highly correlated to, road characteristics. Furthermore, Simwanda assumed that air resistance is negligible for chip truck travel at low speeds on forest roads (Simwanda *et al.*, 2015). On roads of high quality, posted speed limits will determine operating speed, and the impact of air resistance on fuel consumption will be captured by the other variables in the models.

The experimental design allowed the detection of even small effects and provided an additional opportunity to explore the statistical consequences of different road section lengths. Given that the test track of 320 km could be divided into road sections of different lengths, varying section lengths gave an additional opportunity to investigate the effects of the registered variables. For example, the impact of curvature, surface roughness and integrated gradient on speed increased with longer road sections, while the impact of single lane decreased. The increasing effect of integrated gradient with road section length is logical, as Ig describes all vertical movements on an undulating road section. The highest coefficients of determination (R^2) for road sections of 1000 to 5000 metres may be explained by the fact that longer sections were subject to less impact from adjacent road sections and road section edge measurement effects. On the other hand, longer road sections mean fewer observations and less variation in the material. Based on this experience, longer road sections (1000-2000 metres) are recommended when using the models.

The study captured the variation in the forest road construction measures recommended by the Swedish Forest Agency (Gunnarsson *et al.*, 2011). Under typical transport conditions, high-standard roads dominate, and difficult conditions represent only a small proportion of the total assignment. The roads used in this study had greater gradient, curvature and surface roughness than typical roads, which explains the higher fuel consumption compared to earlier studies: 58 litres/100 km (Brunberg *et al.*, 2009) and 59.6 litres/100 km (Forsberg, 2002).

By using only one truck and one driver throughout the study, the impact of truck performance or driving style was eliminated, allowing us to focus on the other variables. The studies were conducted during two short periods, quite close together, so wear and tear on the truck was minimized. Although each of the study days was long, regulations for driving and rest time were followed, and the experienced driver did not exhibit fatigue.

7.3 Improved modelling for transport costs and pricing

Information on time and fuel consumption is important from a cost modelling perspective (Holzleitner *et al.*, 2011). Time and fuel consumption represent approximately two-thirds of the logging transport cost in Sweden, and the introduction of heavier and longer truck combinations, with their greater momentum, makes these issues even more important. The results from Papers I and II will help to improve the general understanding of the effects of road conditions on log truck performance.

One example is described in the paper, where the impact on fuel consumption and roundtrip time for logging trucks is estimated using the proposed models for assignments on roads of low difficulty compared to high difficulty (Table 12). If these values for speed and fuel consumption are entered into the vehicle operation cost model TRANSAM (Langvall & Löfroth, 1988), the cost per tonne for a 60-tonne truck and trailer combination with a payload of 37 tonnes, increases from SEK 95 for easy road conditions to SEK 130 for difficult road conditions. Of this 38% increase in costs, fuel accounted for approximately one-third and time consumption two-thirds. The considerable increase in cost due to road conditions underlines the importance of this knowledge, and indicates that the effect of road characteristics on both operating speed and fuel consumption should be incorporated in cost and pricing models.

7.4 Improved road investment calculation

One important tradeoff to consider in forest road development and management is the one between investments in roads and transport costs (Della-Moretta & Sullivan, 1975). The findings in studies I and II will help to improve cost/benefit analyses related to forest road design, construction, improvement and maintenance (Löfroth, 2014b; Gunnarsson *et al.*, 2011). Where is the breakpoint between the costs for a given road construction project and maintenance level, compared to the gains from more efficient transportation? How much faster will the truck be able to travel if a road section is improved in terms of curvature, gradient and road surface roughness, and how much will fuel consumption be reduced? Would grading and improved alignment pay off?

There are several examples of activities that will benefit from improved models describing fuel and time consumption. *(i)* Some forest companies in northern Sweden have improved road sections to make transport of large volumes more efficient. These types of investments can now be evaluated, and others may follow. *(ii)* In the cost/benefit analysis prior to road construction, the savings in shorter transportation by forwarder during subsequent cuttings is usually compared to the cost of road construction (Stoor, 2008). Traditionally, transport savings for machinery and staff are also included. Increased knowledge about the impact of road characteristics in transport efficiency can now be another parameter to consider to improve road network planning. *(iii)* Support systems for strategic planning have been developed to identify bottlenecks in the road network (Flisberg *et al.*, 2014; Karlsson, 2005). These systems are matching information about available harvesting volumes in a region with industry demands, and more accurate information about time and fuel consumption will refine these systems.

7.5 Augmented road data network for improved routing

In Paper IV it was shown that the basic road data network could be expanded by introducing more nodes and arcs, and arcs representing illegal turns and acute angles between roads at intersections were removed. The proposed methodology for constructing an augmented network makes it possible to generate routes that follow all rules with regards to turning, i.e. ignoring forbidden and impossible turns. The increase in average distance when implementing forbidden and impossible turnings was 40 metres compared to the average distance of all unique logging routes in 2012. This will have little impact on remuneration to the haulier (approximately SEK 1/assignment), but it will increase confidence in the system when the routing is also correct on the map displayed in the cab of the truck.

Average distance also increased when realistic resistances for time and fuel consumption at intersections were introduced, which is natural when intersections are avoided. In all cases, individual distances could both increase and decrease. This is because CRF looks for the combination of arcs that minimizes total ‘cost’. When an arc is removed, or an extra ‘cost’ is applied on an intersection, CRF searches for a route that takes this new situation into account. The new route may be the same, but may also be longer or shorter than the original route. The system minimizes the total ‘cost’, not the distance. Interesting to note is that time spent at intersections was 8-9%, and fuel consumption as high as 13-15%, which explains why truck drivers want to avoid intersections where possible.

Since the network includes arcs for all turning options, the ‘cost’ of turning onto roads of lower quality can be added. By increasing the ‘cost’ of leaving a better road for a short-cut on a lower quality road, the number of these turnings decreased, indicating that the current solution uses many short-cuts. The study shows that the number of these turnings can be reduced without significantly increasing the distance.

Several available implementations use a dynamic representation of the turning options, and are typically based on heuristics motivated by shorter solution times. Our studies show clearly that our solution manages these situations better, and, although the solution times increase by a factor of four when the augmented network is used, it is still within the time requirement for a response in the web system.

In an augmented data network, much more detail can be applied to turning restrictions at intersections. Increased time and fuel consumption due to deceleration, waiting and acceleration, depending on whether the truck is going straight on or turning left or right, can now be considered. If the number of stops and turns are regarded as a penalty, and certain 'costs' are directly applied to turning arcs in intersections, the route generated may differ considerably. This is one aspect that has been requested by drivers, and is now possible. However, there is a need to study in more detail how the stopping and turning times can be estimated more accurately. To apply the 'costs' directly on the turning arcs as in this study is one way, but another approach would be to classify turning arcs in intersections of varying design in terms of deceleration, waiting time, acceleration and increased fuel consumption. Weights can then be assigned to these classes through the inverse optimization process.

7.6 Improved planning

The results from this study have increased knowledge of how fuel and time consumption is affected by, for example, truck weight, road topography and various types of intersections. This, together with accurate distance measurement, is crucial information in different kind of planning situations on strategic, tactic and operative levels.

Fuel consumption, and resulting emissions from transport, is a growing concern and has become an important field of transport research and development (Sena *et al.*, 2011; André *et al.*, 2009). Green Vehicle Routing Problems (G-VRP) are formulated and solution techniques are developed to aid organizations in handling different situations. Recent reviews describe current models, methods and applications in this field (Demir *et al.*, 2014; Lin *et al.*, 2014; Park & Chae, 2014). Studies have shown the possibility to minimize fuel consumption in a fleet instead of the traditional planning target to minimize distance or driving time (Kopfer *et al.*, 2014; Oberscheider *et al.*, 2013). G-VRP can also be used for alternative fuel-powered vehicle fleets in overcoming difficulties that exist as a result of limited vehicle driving range in conjunction with limited refueling infrastructure (Erdoğan & Miller-Hooks, 2012).

Operative route planning on daily and weekly levels is a real challenge. Many restrictions are to be considered in order to complete the delivery quota and improve transport productivity by, for example, increased back haulage. Besides climatic factors and temporary restrictions in the road network, shift changes, driving and rest periods, opening hours and current queue situation at the recipient point must be considered. This study has contributed to this planning by improved estimations of turnaround time.

7.7 Use of key routes for weight setting under different CRF applications

The key routes describe best practice in logging truck routing, and the assignment of weights in the CRF system is entirely dependent on them. Here, both the strength and a possible weakness of the system can be found; the key routes describe how operational routing is done, but the idea of what is the best routing varies. Initially, the assignment to create key routes was given to all forest companies across the country, so many people were involved in the work. The subjective nature of the process means that the key routes may vary greatly in terms of optimality. One example was that the concept of routing differs between northern and southern Sweden. This led to discussions about whether to have more than one weight setting. The decision was to have a single setting for the whole country, which now facilitates transport activities between all parts of Sweden. At the same time, while it is positive to cover all different perceptions of what is the best route, differences in views remain, which can explain why we do not find a weight setting that is compatible with all key routes.

The key routes are updated continuously in response to changes in the road network, but they have also been revised several times. Before the curvature and hilliness features were implemented, alternative key routes were circulated for evaluation, and some of them were adopted. This improves the system by eliminating possible incorrect routes, and keeps CRF up to date, but the process is rather cumbersome. A more flexible tool may need to be developed to enable sensitivity analyses.

With new models describing fuel and time consumption related to road characteristics, there is now great opportunity to reduce fuel consumption, CO_2 emissions, or travel time. This will become increasingly significant in the light of global warming. Furthermore, the relationship between time and fuel consumption may change over time, so traditional route choices may need to be reconsidered.

The current weight setting in CRF generates distance and route for a loaded truck from landing in the forest to recipient point, under summer conditions. In the future, it would be useful to generate the reverse route (from recipient point to landing) used when the truck is empty. The lower weight would present other network opportunities, and time on that route could also be estimated to support operative planning.

A further development would be to automatically generate routes between landings for use in assignments where several landings must be visited to create a full load, or for a sequence of assignments during a certain time. The latter would provide valuable input in planning systems. Better planning could increase and realize the full potential in back haulage (Carlsson & Rönnqvist, 2007), help drivers not familiar with the region to navigate, and consider restrictions such as slot times and queues at industries and statutory driving and rest periods.

Other possible applications that could be incorporated in CRF are heavier and longer trucks, such as 74 and 90 tonnes, routing under winter conditions, routing for trucks equipped with CTI, or routing if kilometre taxes for heavy vehicles using public roads are applied. All these examples involve different routing solutions that require unique weight settings.

The key routes are a snapshot of routing under prevailing conditions, but do not say much about routing under different conditions. Implementing changes in weight settings would mean that the key routes must be revisited and multiple key routes established, which is a major undertaking. Also, it is not obvious that changes of this type, which may be just minor adjustments to the current route, will appear when new key routes are drawn.

Today’s key routes are based on many years of experience, and the devisors of the key routes may not be capable of directly altering routing based on new conditions. Some of these applications may be managed as adjustments in the network, such as CTI, where certain roads are available for trucks equipped with CTI but not for other trucks. Winter application of CRF could be developed by eliminating arcs that are undesirable under winter conditions, for example steep slopes.

7.8 Improvement of NVDB data quality

Paper III confirmed that the data quality in NVDB is not accurate enough to meet the requirements when calculating vertical and horizontal curvature in the proposed method. Ways had to be found to reduce data errors and to manage identified deficiencies in the road data. Filtering, and the use of spline functions that smooth the coordinate sequence, proved useful, as well as a method to calculate acute turning angles by using the adjacent coordinates at an intersection. The use of LIDAR data in improving data quality was also successful.

All planning – strategic, tactical or operative – is dependent on reliable and complete data about the road system, so that travelling distance and fuel and time consumption can be calculated accurately. Methodology to improve data quality in NVDB has been suggested, including the use of LIDAR data (Craven & Wing, 2014), and the development and implementation of sensors carried by man or truck can lead to data retrieval and maintenance taking a new direction.

This study has identified several urgent data quality needs. *(i)* Improved frequency and accuracy regarding the x, y and z-coordinates, which often differ, both laterally and vertically. Coordinate accuracy and frequency is vital in several situations, e.g. calculation of hilliness and curvature, and fuel consumption and operating speed estimations. *(ii)* Complete information about road width, which is often lacking and is important in calculations including operating speed estimations. *(iii)* Identification and incorporation of impossible turns in intersections to improve routing, and suggest routes that are in compliance with current regulations. *(iv)* Complete and reliable bridge information to improve routing and avoid accidents. Information about most of the bridges on the private road network is currently lacking in the NVDB, both in terms of placement and bearing capacity. This can cause problems and time loss for truck drivers when they realize that the suggested route passes a bridge with a weight limit lower than the truck weight, with the consequence that the driver must reverse and find an alternative route.

7.9 Improved remuneration system

Logging transport is paid per assignment, and the remuneration is based on the payload and distance between landing and mill. When a route is chosen by CRF, the system finds the combination of arcs in the network that minimizes the total resistance (‘costs’). In many cases, two (or more) routes are very similar, in terms of total resistance points, but have different lengths. Examples are given in Figure 20, where the black and orange routes have the same resistance, which means that CRF considers them comparable. However, the length differs by 35-50%, which has a major impact on remuneration to the hauler.

Figure 20. CRF choses the minimum-cost route. In this example, the orange and the black route from landing to mill are similar in terms of resistance points, but they differ in length.

Figure 21 shows another example where three assignments have the same length, but the resistance points differ by up to 60%. Here the haulers would receive the same remuneration, but CRF shows that the actual work differs. When the routes in these examples are studied, what is clear are the variations in the proportions of gravel roads, narrow roads, hilliness and curvature, which have a significant effect on time and fuel consumption.

Figure 21. An example of three assignments similar in length, but varying resistance points according to CRF.

A conclusion of the examples above is that distance is a poor measure of the work performed during a logging assignment. CRF better describes the actual work performed because it balances several objectives. Introducing an estimation of fuel and time consumption at arc level in CRF (and not just for curvature and hilliness as today) would be an improvement. This could be done directly, or as features with corresponding weights. Initial analyses have indicated that the CRF resistance points could also be used in calculating remuneration to the hauler.

This would produce a remuneration system that considers the main elements of transport costs, time and fuel consumption, together with distance travelled. Alternatively, CRF could be used to generate a route, and the actual remuneration could be based on resistance points, calculated time and fuel consumption. Regardless of which of those systems is chosen, the outcome would be fairer in the sense that geographical and topographical differences would be reflected in remuneration, and there would be fewer discussions about route choices generated by CRF. Each individual assignment could be remunerated more accurately compared to the current situation, where remuneration according to transport environment is determined during the annual contract negotiations, and then applied as an average on all assignments, irrespective of conditions.

7.10 Success factors for CRF

Important lessons learned from the development of CRF and its success factors can be summarized in the word ‘collaboration’. Everything concerning the system has been made possible through the collaboration between end users, forest and haulage companies, managers at SDC, and developers at Skogforsk. A common driving force has been to create an efficient, transparent and objective system used by all stakeholders. This has simplified the procurement of transport services, automatized administrative tasks and reduced costs.

Collaboration was also crucial for the creation of NVDB, the national road database. The forestry sector, responsible for the private road network which represent more than 80% of the total network in Sweden (Flisberg *et al.*, 2012), created an organization for collection and reporting of road data to the NVDB. Also, the system development was done in cooperation. With the NVDB in place, the Council for Forest Logistics, representing all forest companies, commissioned SDC to start the development of CRF. The dual development and testing between SDC, the IT-company Triona and Skogforsk has also been very beneficial for the overall implementation process.

Another key factor for the success of CRF is that the system is constantly subjected to evaluation by the end users. Key routes from forest companies and transporters in Sweden representing best practice came to play an important role. Another important channel for this evaluation is the deviation reports submitted by end users. They are, together with a sustained interest in the continued development from the forest companies, the origins of the success of the system today.

Other countries have shown interest in using the methodology behind CRF, and currently initial trials to analyse the system are ongoing in Norway. A prerequisite to exploit the system's full potential is the availability of well-described road data covering all types of roads used by the haulers, and several examples of best-practice routing. In the case of limited access to road data, the system can be implemented, but with certain limitations. Fundamental requirements on a road data network are descriptions of road classes and the geometrical extension in the landscape. From this information, it is possible to develop features describing hilliness and curvature, as well as fuel and time consumption.

7.11 Concluding remarks

This thesis has focused on improvements to Calibrated Route Finder. This has been done by developing techniques to include features describing vertical and horizontal curvature, features that have been implemented and are now operational in the system. An augmented network has been developed, and has proved useful in handling illegal and impossible turns in intersections, including descriptions of time and fuel consumption. Important contributions are the studies and models of how different road characteristics and truck weight affect fuel and time consumption for logging trucks.

The goal for CRF, and therefore the Swedish forestry sector, is to identify logging truck routes that balance both qualitative and quantitative objectives. CRF is not seeking the shortest or fastest route, and with its inherent consideration of social values such as road safety, working environment, and avoidance of traffic sensitive areas in built-up areas, CRF has now been strengthened by inclusion of new features that consider stressful situations for the truck drivers.

Lead time from concept, through development and analysis, to full-scale implementation in CRF is very short, largely due to the close cooperation between the different parties involved in the system. It has enabled a continuous demand-steered improvement of the system by introducing new features, so use of the system has grown quickly and considerably.

The development of CRF has resulted in a paradigm shift from manual, imprecise and unilaterally determined routes to automatically generated routes decided jointly between the parties. Today almost all forest companies are affiliated to the system, and they experience it as a major benefit. It has enabled standardization, promoted collaboration, and reduced transport costs, which has strengthened the competitiveness of the Swedish forest industry on the international market.

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