# ETT – A MODULAR SYSTEM FOR FOREST TRANSPORT A three-year roundwood haulage test in Sweden

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## Summary

A logging truck, 30 m in length, and with a maximum gross combination weight (GCW) of 90 tons, was tested over more than three years in the northern part of Sweden. On two round trips, the volume of roundwood that this truck can haul is equivalent to that carried by three conventional Swedish 60-ton trucks. The results show that the truck reduces costs and  $CO_2$  emissions by 20%. No negative impact on road safety was observed and road wear was not increased as the weight was distributed over more axles. The distance covered by the vehicle was 900,000 km and the transported volume 160,000 m<sup>3</sup>. The studied vehicle was run on a 170-km route from a terminal in the north down to one of SCA's large sawmills in Piteå.

The project also included a study of two 74-ton vehicles within the maximum permitted length of 24 m under Swedish legislation. These vehicles were tested in the southwest of Sweden. One of them was equipped with a crane and the other was loaded by a separate loader or from the crane truck in a staging system. Results showed that both emissions and transport costs were reduced by approximately 10%. Environmental effects, traffic safety and technical development have been focus areas in both studies.

The ETT project, initiated by Skogforsk in 2006, encompasses a broad collaboration between researchers, the Swedish Transport Administration, the forest sector, The Swedish Association of Road Transport Companies, Volvo, the automotive industry and the private road associations.

**Keywords:** High Capacity Vehicle, Transport efficiency, load capacity, traffic safety, road infrastructure, bridge, EMS (European Modular System), logging truck, fuel consumption, CO<sub>2</sub> reduction.



Figure 1 - The studied vehicle, loaded with 65 tons at one of the terminals

# 1. Introduction

This project is an environmental study with multi-disciplinary implications. Road transport is responsible for a growing share of total  $CO_2$  emissions. In order to reverse this trend, the specific  $CO_2$  emission per transported unit needs to be decreased. This can be attained by increasing the load capacity per vehicle.

In the past decades, Sweden has allowed increased weight on the vehicle combinations. Present Swedish legislation allows a gross combination weight of up to 60 tons and a vehicle combination length up to 25.25 m. If the amount of goods transported per vehicle is to be increased, the maximum permitted dimensions also need to be increased. The first step is to increase the maximum weight within the permitted length. The second is to increase both permitted length and weight. Special permission is needed to get access to public roads for High Capacity Vehicles (HCV).

The present infrastructure is mostly unsuitable for wider or higher vehicles, but in many cases longer combinations can be adopted into existing infrastructure. Greater weight can be distributed over more axles to ensure the weight on each axle is not increased. Gross combination weight can affects bridges also when the free span of the bridge does not exceed the vehicle length.

Sweden has a national target to reduce  $CO_2$  emissions by 40% by 2020 in relation to the 1990 level. Timber transport is very significant in attaining this target since it comprises approximately 25% of all road transports in Sweden. The average distance of Swedish timber transport is 100 km. Transport by rail comprises approximately one third of the transport work within Swedish forestry, [9], but in most cases the transport requirement is not from a terminal with railroad access. Consequently, environmental improvements within the road transportation system must be made in order to reach the target for  $CO_2$  reduction.

In 2006, Skogforsk initiated a project aimed at lowering the total number of timber transports needed in Sweden and reducing the associated diesel consumption and emissions. This was to be attained through advances in transport technology and logistics, but also by using longer vehicles with higher gross weights. No negative effects in terms of road wear or road safety could be tolerated. However, pre-studies of literature indicated that there would be no such effects [13]. The present study started in 2007 when the vehicle industry joined the forest industry to investigate how to radically reduce the  $CO_2$  emissions from timber transport.

Current conventional timber transport vehicles in Sweden and Finland have a gross weight of 60 metric ton and are up to 24 m long. They generally comprise a three-axle truck with space for one stack of wood, and a four-axle full trailer that carries two stacks. This can be compared to the European standard of 18.75 m and 40 tons. Longer vehicles (over 25 m) are commonly used in, for example, Australia, Canada and South America. They are often restricted to specific roads or conditions [7].

The name of the project is ETT, a Swedish acronym for *One More Stack* ('En Trave Till'). The project is a collaborative venture between Skogforsk, the Swedish Transport Administration, the forestry companies, the Swedish Association of Road Transport Companies, Volvo, the automotive industry and the private road association.

## 2. Aim and objectives

The aim of the project was to study and evaluate the potential for and consequences of greater gross weights and vehicle lengths for timber transports. Studies examined effects on diesel consumption, emissions of greenhouse gases, transport costs, road safety and road wear.

The objective of the ETT project was to decrease  $CO_2$  emissions from timber transport. Early in the project it became apparent that the focus would be to develop, evaluate and implement a modular system for timber transports that would improve efficiency and reduce environmental impact, without compromising road safety, road standard or driver environment. The primary target was to achieve environmental benefits from reduced fuel consumption, while improving efficiency and reducing costs in the haulage of timber. A more efficient use of the existing road infrastructure through higher-capacity vehicles was also a long-term ambition.

## 3. Research method

The project covered several research areas, such as environment, technology, economics, and risk analysis.

Hypothesis: Increased load gives reduced CO<sub>2</sub> emissions per transported cargo unit.

Boundary conditions: In order to gain acceptance, the high-capacity vehicles need to be as good as present vehicles in terms of safety and road wear. Vehicle performance has to meet certain standards in order to be considered safe. Safety should also be evaluated from the perspective of how a longer vehicle interacts with the normal traffic. Cost of operation must not increase and will preferably decrease upon full implementation.

## **3.1** Concept evaluation and design

Two different areas were selected for the tests. One was in the northeast of Sweden with paved roads and flat road conditions, and the second was a hilly area in the southwest with road quality ranging from gravel roads to highways. These driving settings dictated the conditions for the concept evaluation.

Concept evaluation: In first part of the ETT project all project members contributed to the process of developing different vehicle configurations. Six concepts were defined, A-F, as shown in Figure 2. Concept G is the reference vehicle, a traditional Swedish timber truck.

							Total					
	Weights in metric tonnes	Unit 1	Linit 2	Unit 3	Unit 4	Total tara	weight on road	Max load	Load	Combination		
	Weights in meale tonnes	Tractor	Link	Link	Semitrailer	weight	onroad	onroud	Quate			
Α	Tara weight	9,5	4,6	4,6	5	00.7	00	00.0	74%			
	Max total weight on road	26	24	24	24	23,7	90	66,3		000 000 000		
		Truck	Dolly	Link	Semitrailer							
B	Tara weight	11,9	2,4	4,6	5	23.0	90	66 1	73%			
	Max total weight on road	26	18	24	24	25,5	30	00,1		lo = 00 = 00 = 000		
		Tractor	Long-Link	Semitrailer								
C	Tara weight	13	8,5	5		26.5	80	53.5	67%			
	Max total weight on road	32	24	24		20,5	00	55,5		40-000 000		
		Tractor	Link	Semitrailer								
D	Tara weight	9,5	4,6	5		10.1	74	5/ 0	74%			
	Max total weight on road	26	24	24		13,1	74	54,5		00000000		
		Truck	Dolly	Semitrailer								
E	Tara weight	15	2,4	5		221	68	15.6	67%			
	Max total weight on road	26	18	24		22,4	00	43,0		-0 -00 -000		
		Truck	Dolly	Semitrailer								
F	Tara weight	17,5	2,4	5		24 9	74	49.1	66%			
	Max total weight on road	32	18	24		24,5	14	40,1				
_		Truck	Full Trailer									
G	Tara weight	15	6,3			213	60	387	65%			
	Max total weight on road	26	36			21,5	00	00,7				

Figure 2 - Vehicle concepts in the first evaluation

Criteria for concept evaluation were at this stage: payload, tara weight and vehicle agility (off-tracking).

All concepts were designed to comply with permitted axle loads in Sweden, in combination with a maximum total weight of 90 tons.

The remaining vehicle combinations were analyzed with respect to dynamic stability, swept path width and road wear.

Dynamic stability and swept path width (SPW) were analyzed in non-linear mathematical vehicle models with longitudinal, lateral and yaw degree-of-freedom. Roll degree-of-freedom was not considered as its influence is not significant and the purpose was to compare different vehicle combinations. Respective axles in the different vehicle combinations were equipped with identical tires to enable accurate comparisons.

Methods according to ISO 14791 [5] were used for the stability analysis. The measurement used to compare the different vehicle combinations was the maximum rearward amplification (RA) of yaw velocity in a path-following lane change. For some combinations, it was also relevant to use the yaw damping of the lightest damped mode during free oscillations.

The swept path width is determined in a 90-degree turn with an outer radius of 12.5 m at low speed. It was defined as the maximum distance between the outer reference path and the innermost path described by any point of the vehicle.

In order to quantify the road wear the fourth power rule was used. This gives the number of equivalent standard-axle loads,  $P_0$ .

$$N = \sum \left(\frac{P_i}{P_0}\right)^n \text{ where } P_i = \text{actual axle load, } P_0 = 10 \text{ t, n} = 4$$
(1)

If the gross combination weight is normalized, vehicle combinations with different gross combination weights can be compared.

### 3.2 Verification method for main hypothesis – production and emissions

Emission of  $CO_2$  is directly proportional to fuel consumption. Fuel consumption was measured by calibrating estimated injected fuel using the actual filled fuel volume. This allows accurate measurement of fuel consumption on sections of journeys or whole journeys.

During the practical test, vehicle speed, load and fuel consumption were continuously monitored using the fleet management system, Dynafleet. Skogforsk analyzed costs, production and fuel consumption based on the data provided.

In three comparative studies of fuel consumption, the truck of the 60-ton version of the ETT vehicle served as reference vehicle. In one of the studies, the truck pulled a conventional 4-axle full trailer, and in the two other studies pulled a dolly and trailer. The comparative studies of the 90- and 60-ton vehicles were carried out under similar conditions and with the same driver.

### 3.3 Technical development assuring vehicle performance

The manufacturers were responsible for technical evaluation and development during the project. Vehicle stability, start ability, grade ability, swept area, weight control, anti-jackknifing and breaking distance had to meet certain standards. European regulations on coupling equipment do not cover more than one articulation point, so special attention had to be paid to the coupling forces.

### 3.4 Verification of traffic safety

Prior to the testing period, a meta-analysis of the difference in accident risk between long and short truck configurations had been carried out by Wåhlberg [13]. Mean values of the risk ratios between long and short truck configurations were calculated from more than 20 studies. This was the first part of the traffic safety evaluation. During the test period, further studies of traffic safety were carried out.

Skogforsk observed 700 overtakings of the 30-m vehicle. In five cases the driver of the overtaking car was interviewed immediately after the overtaking maneuver in order to determine the overtaking driver's reaction to the longer vehicle. The 30-m vehicle was fitted with a sign reading "long load".

VTI (the Swedish National Road and Transport Research Institute) carried out a safety study in four parts. The purpose was to investigate whether the introduction of longer and heavier vehicles has an effect on safety on Swedish roads, especially in terms of overtaking. The empirical studies included a focus group interview with drivers of heavy trucks, an interview study with drivers of extra-long trucks, a simulator study and a field study. The entire study is presented in the report *VTI - Trafiksäkerhetseffekter vid införande av längre och tyngre fordon – en kunskapsöversikt [4]*. The results will be briefly summarized in this paper.

#### 3.5 Verification of the effect on road wear

The Swedish Transport Administration monitored road wear and the load on bridges. Analyses were carried out using the Percostation system - a tool for monitoring bearing capacity in road construction. Sensors, providing real time data of the impact on different road layers, were used.

Reliable load control is essential in order to verify that the load restrictions are not exceeded in terms of either load per axis or total load. This affects the wear on the road. Evaluation of the load control system was therefore included as a study within the project.

### **3.6 Project management**

The project was managed by Skogforsk in close cooperation with the industry and applicable authorities. The technical development and construction process of the three vehicles was led by Volvo in cooperation with a large number of manufacturers. The 90-ton vehicle commenced operations in January 2009, and the practical test with the two 74-ton vehicles started in August the same year. The Swedish Transport Agency granted permission for the tests. The Swedish Transport Administration was responsible for evaluating the safety studies.

A group was formed to manage cases of unforeseen events. The group comprised people from the participating authorities and companies, and was divided into an inner circle and an outer circle. The role of the inner circle was to become aware of deviations or accidents and report to the outer circle. The role of the outer circle was to assess and disseminate relevant information.

### 4. Results and conclusions

### 4.1 Concept evaluation and design

The results from the first evaluation of the concepts shown in Figure 2 are listed below. The 4 selected combinations are then described in more detail under separate headings.

A: Load 66 tons in combination with load quote 73%. Good axle load distribution but severe off-tracking in roundabouts and crossings. Concept on hold.

B: Load 66 tons in combination with load quote 73%. Good axle load distribution, acceptable off-tracking in roundabouts and crossings. Concept accepted.

C: Load 54 tons with acceptable load quote 67%. Load area designed for more load, which cannot be used due to poor axle configuration. Severe off-tracking in roundabouts and crossings, Concept on hold.

D: Load 54 tons in combination with load quote 74%. Already common vehicle configuration with low off-tracking in roundabouts and crossings. Concept accepted.

E: Load 46 tons with acceptable load quote 67% of total weight at max permitted weight. Good axle load distribution, common standard configuration with low off-tracking in roundabouts and crossings. Concept accepted.

F: Load 49 tons with acceptable load quote 67%. Good axle load distribution, better offtracking in roundabouts and crossings compared with traditional Swedish timber truck with full trailer combination (Concept G). Concept accepted.

G: Traditional Swedish timber truck combination, truck and full trailer, Max permitted weight 60 ton and payload with attached crane 39 tons, load quote 65%. Concept G is reference in this study.

The three chosen combinations: B, E and F were built and tested. The various units for the three vehicle combinations were constructed at the selected manufacturers. Each unit does not in itself deviate from present vehicles on account of the modular system chosen. High-capacity combinations are achieved through coupling. However, a number of special adaptations were made to meet the boundary conditions, such as a completely new braking control system for truck and multiple trailers.

## ETT: Truck–Dolly–B-semitrailer–Semitrailer (B in Figure 2)

This vehicle combination, ETT, is a configuration based on the modular system, which has not been used previously on Swedish roads, described in [1], [6]. It consists of a rigid truck, a converter dolly and the two trailers in a B-double, a B-semitrailer and a semitrailer. A B-semitrailer is also called a link. The total length of the combination is 29.5 m, and the rig was loaded with four stacks of timber. If the load modules had been full length, 7.82 m and 13.6 m respectively, the total length would have been 33.8 m. The axle/bogie loads, axle distances and the coupling distances are shown in the table below. The axle distance is the distance to the following axle. The coupling distance for the motor vehicle is the distance from its first axle to the center of the coupling. For the trailers it is the distance from the last axle to the coupling center. The loads are given in kg and the lengths in mm.



Figure 3 - ETT: Truck–Dolly–B-semitrailer–Semitrailer

Laden	Trı	ıck	Dolly B-semi		B-semi		Semi	
Axle/Bogie load (kg)	8800	18100	16800		22100		23600	
Axle distance (mm)	4600	1370	13	1300		1300	1300	1300
Coupling distance (mm)	70	)85 4250		650	8100	1300	88	00

Table 1 - Axle/bogie loads, axle distances and coupling distances

As timber trucks inevitably run 50% of the distance with no payload, it is of interest to minimize fuel consumption and tyre wear also on the return trips. This can be achieved by lifting axles. Axle loads for the case with six lifted axles are shown in the table below. The lifted axles are axle 3 on the truck, axle 1 on the dolly, axles 1 and 3 on the B-semitrailer and axles 1 and 3 on the semitrailer.

Table 2 - Axle/bogie loads with 6 lifted axles without payload

Unladen	Truck		Dolly	B-semi	Semi
Axle load (kg)	4756	7463	2876	4734	3910

## Reference: Truck and full trailer (G in Figure 2)

This is a typical Swedish vehicle combination, traditionally used in the forestry sector. It was used as a reference in terms of performance. The total length is 22.4 m, and weights and dimensions are shown in the table below.



Figure 4 - Truck and full trailer without crane

	Tı	Trailer				
Axle/bogie load (kg)	7500	18500	1650	0	7500	
Axle distance (mm)	4900	1370	1350	50 6270 136		
Coupling distance (mm)	7	12100				

 Table 3 - Axle/bogie loads, axle distances and coupling distances

# ST-Tractor: Tractor–B-semitrailer–Semitrailer (D in Figure 2)

This vehicle combination is a 'B-double', which is a modular combination used in Sweden since 1997. Weights and dimensions are shown in the table below. The total length is 22.3 m.



Figure 5 - Tractor-B-semitrailer-Semitrailer

	Tractor		B-s	semi	Semi	
Axle/bogie load (kg)	6600	17100	22	100	00 23600	
Axle distance (mm)	3200	1370	1300 1300		1300 1300	
Coupling distance (mm)	3550		8100 1300		8800	

ST-Crane: Truck–Dolly–Semitrailer (F in Figure 2)

This is another modular combination already used, principally a truck and full trailer. The motor vehicle has four axles. The total length is 24 m.



Figure 6 - Truck–Dolly–Semitrailer

Table 5 - Axle/bogie loads, axle distances and coupling distances

	Truck		D	olly	Semi		
Axle/bogie load (kg)	8000	240	24000 17500		500	23500	
Axle distance (mm)	4100	1370	1380	13	300	1300	1300
Coupling distance (mm)	nm) 9030			4150	650	845	50

## Dynamic stability

The left graph below shows the yaw velocity responses of the ETT combination in a single lane change at the excitation frequency 0.3 Hz, where the motor vehicle is following a path with a maximum lateral acceleration of 2 m/s2. The right graph shows the free oscillations of the last articulation angle, from which the yaw damping was calculated. The ETT combination appears to be very well damped.



Figure 7 - Yaw velocity and relative damping for vehicle configuration B, fully loaded

The two graphs below show how the rearward amplification of the laden and unladen vehicle respectively is influenced by the excitation frequency. Although six axles are lifted in the unladen case, the rearward amplification appears to be lower than in the laden case.



Figure 8 - Yaw velocity gain vehicle configuration B (left laden, right unladen)

Tab	le 6	<b>-</b> ]	Maximum	rearward an	nplification	(RA	) of all	vehicle	combinations
						•	,		

Vehicle comb	B (ETT)	B (ETT) unladen	G (Reference)	D (ST-Tractor)	F (ST-Crane)
RA (-)	2.01	1.93	1.96	1.39	2.12

The ETT combination appears to be very close to the reference combination in terms of stability. Combination F is somewhat worse while combination D, the ST-Tractor and the B-double, is outstanding. The driver's perception from the test period is that both the ETT and ST vehicles are more stable than regular timber trucks.

#### Swept path

The swept path of the ETT combination is seen in Figure 9. The left graph below shows the swept path in a 90-degree turn on a 12.5 m radius. The right graph shows a 180-degree turn on the same radius. The latter case indicates that it should be possible to turn the vehicle in a 26 m wide turning place. This was also verified in practical tests.



Figure 9 – Swept path for the ETT combination with R=12.5 m. Left: 90°. Right: 180°

Vehicle comb	B	B G		F
	ETT	ETT Reference		ST-Crane
SPW (m)	7.79	6.27	7.10	5.90

Table 7 - Swept path width (SPW) of all vehicle combinations

The ETT combination appears to require approximately 24% more space to turn than the reference combination. Combination F requires less space than the reference vehicle combination. Consequently there is an inverse relationship between stability and path following. The ST-Tractor B-double, vehicle combination D, which has very good stability, is approaching the SPW of the ETT combination.

## Road wear

Table 8 shows the number of equivalent standard axle loads, according to equation 1, normalized with the gross combination weight (kg).

Table 8	– Norm	alized n	umber o	f equival	ent axle	loads	for the	e selected	combinations

Vehicle combination	B (ETT)	G (Ref)	D ST-Tractor	F ST-Crane
Normalized number of equivalent axle loads $\cdot 10^6$	56	62	46	57

The road wear from the ETT combination appears to be less than from the reference combination. Combination D, the ST-Tractor and the B-double, causes the least road wear.

# The modular system

The modules used for the vehicle components are shown in Figure 10. The EMS module lengths are 7.82 m and 13.60 m respectively. For timber application, the modules are shorter, 6.5 m and 12 m respectively.



Figure 10 - The modular system for timber transport

### 4.2 Verification of main hypotheses - Production and emissions

#### ETT vehicle: 90 ton and 29.5 m

During the test period between January 2009 and June 2012, the ETT vehicle drove a total of 900,000 km and transported approximately 160,000 cubic meters solid volume from Överkalix to Munksund in Piteå. The ETT vehicle improved transport efficiency, because the payload of each vehicle is 50% greater than that of a conventional 60-ton vehicle. Two ETT vehicles are as productive as three 60-ton vehicles.

Three years of testing show that diesel consumption of the ETT vehicle was an average of 22% lower per transported unit compared to a 60-ton vehicle performing the same transport task. The consumptions are shown in Table 9.

Table 9 - Average	fuel consum	ption for the tot	tal roundtrip	(340 km).
				· /

	l/ton·km	l/km	l/ton
ETT vehicle, 90 ton	0.016	0.54	2.6
Reference vehicle, 60 ton	0.019	0.43	3.3

Fuel consumption, and thereby carbon dioxide emission, varies during the year, with a peak during the winter season as seen in Figure 11. When the rig was fully-loaded, fuel consumption varied between approximately 0.6 and 0.7 liters/km, depending on the season. When empty, fuel consumption varied between 0.35 and 0.43 liters/km, depending on the season. The difference in fuel consumption between driving empty and driving fully-loaded was approximately 0.27 liters/km.



Figure 11 - Fuel consumption over 18 months

Subsequent measurements of the ETT vehicle show that a further 8% fuel was saved when 5 out of 11 axles were lifted on the empty return trip. This meant a total of 3% additional savings on the whole transport cycle.

The economic calculation shows that the increased production capacity of 50% cuts the transportation cost by 20%. The capacity in the existing road network has been suitable for the ETT vehicle. The system thereby demonstrates an interesting potential for increasing road transport efficiency without investments in infrastructure.

## ST vehicle: 74 ton and 24 m

The two ST vehicles drove a total of just over 500,000 km and transported 190,000 cubic meters solid volume. Of this volume, the ST tractor drove nearly 10,000 cubic meters solid volume loaded with a group loader. From 1 December 2011, the vehicles were driven separately as crane truck and group vehicle.

Since the driving conditions for the vehicles varied significantly between different periods, fuel consumption data showed great fluctuations. The results from measurements during 2010-2011 show an approximate average fuel consumption of 0.042 l/ton·km for the crane truck and 0.024 l/ton·km for the tractor.

In autumn 2010, a study compared fuel consumption of the ST tractor and a conventional group vehicle performing the same transportation task. The results showed that fuel consumption of the ST tractor was 15% less per transported ton.

# 4.3 Technical improvements assuring good vehicle performance.

The tests were carried out in varying topography and road conditions under extreme winter conditions. The 90-ton truck was mainly driven on tarmac and with a maximum slope of 4%. The 74-ton trucks were operated in a hilly environment with slopes often around 10-15%, sometimes even steeper. Vehicles operated both on gravel and tarmac. These settings have been essential for the technical specification of the vehicles.

## **Traction**

For all the trucks, an essential amount of driving took place in snowy and icy conditions. It is important that basic functions are maintained in these conditions. A number of functions were in focus for securing good winter performance, such as better friction through snow pattern on drive tire, sanding equipment and on-spot snow chains. On the ST-Crane, more drive axles were available through hydraulic drive.

The 90-ton combination was also equipped with automatic lift axle control so, when unladen or partly laden, the axle(s) on the trailer(s) lifts from the road, thereby increasing traction and decreasing fuel consumption and tire wear. Five out of 11 axles can be lifted on the ETT vehicle.

# Light construction

The use of SSAB's high-strength steel, Domex 700, was discussed at an early stage to reduce the overall weight. There were some concerns about this since we were working with an

existing traditional design and development time was short. We decided therefore to use 100% Domex 700 in the rear trailer of the ETT combination. The main chassis beams, cross members and all other attachments were made from Domex 700. This reduced the weight of this unit by nearly 300 kg. By using the same material in the link, dolly and in the timber frame on the truck, weight could be reduced by up to 800 kg for the whole combination. These savings can instead be used to increase payload and thereby increase the transport efficiency. [10] [8].

### **Coupling points**

As European legislation does not cover vehicle combinations with more than one articulation point, we paid special attention to design of coupling dimensioning. From Australia we learned that the dynamics of a multi-articulation point road train differs from ordinary truck and trailer combinations. We adopted the Australian rules (ADR) to take this into account. We then measured coupling forces during vehicle operation. These measurements showed us that the forces are generally much lower than those applied in the certification fatigue tests for the equipment installed. In particular the forces due to acceleration, slopes and braking were very moderate. Forces generated by road bumps and potholes were those that had any significance. Models show that forces of impulse character will be attenuated as they propagate through a number of vehicles and coupling points. Consequently, the somewhat smaller design applied through the ADR is motivated. Within ISO a new dimensioning standard is being developed for road trains of the configurations accounted for in the European Modular System. That standard draws on the ADR and is supported by the measurements made within the ETT project. This project has contributed a lot to the understanding of the mechanisms behind coupling forces. The simplified model on which UNECE Regulation 55 is based may eventually need some modifications. [11].

#### Electronic braking system

All trailers in the 90-ton and 74-ton combinations were equipped with Electronic Braking and Roll-over Stability Systems from WABCO, version EBS E. These systems were designed in accordance with ECE R13 and ISO 11992. All trailers could therefore communicate with the truck via CAN bus messages. By using EBS CAN Router, all trailers can be controlled and utilize both the braking and other communication demands. The system responds much quicker than a conventional system and therefore reduces the braking distance significantly. The CAN bus also transfers vehicle data to the driver from all trailers, such as gross weight, thanks to the EBS CAN Router. The Roll Stability System also improves road safety and prevents each part in the combination from rolling over. The system is now in serial production and is successfully used in shorter truck-trailer combinations around the world. [3]

## Load control

The ST-Crane truck, as seen in Figure 6, is fitted with the first type-approved and verified crane scale in Sweden for automatic dynamic weighing of suspended load, i.e. a scale that can weigh a load in movement. The weighing device is manufactured by Intermercato and is type-approved and verified by the SP Technical Research Institute of Sweden. The verification means that the weight data provided by the scale can legally form the basis for invoicing. The scale is based on traditional strain gauge technology. A metal body (load cell) senses the strain, which is registered by several sensors. A signal from the load cell is converted and

interpreted by a unit in the scale. The unit then sends digital measurement data via radio to the crane cab. A hand-held computer shows the load in every stack and the total load on each vehicle.

A verification carried out during the testing period showed that the system fulfilled all verification criteria. The criteria specify the maximum variation allowed for the worst of ten samples. As an example, the maximum variation allowed for 2,000 kg was 15 kg.

On the ETT vehicle, the vehicle itself does the weighing. A system for measuring air suspension pressure is used on all vehicle axles, except on the front axle of the truck where a spring suspension system is used. The load on each axle, as well as the total load, is displayed for the driver. The brakes on the vehicle cannot be applied during the measurements and the whole vehicle should be placed on level ground. [3].

A verification test of the load control system was carried out by Skogforsk and Volvo. Typeapproved and verified vehicle scales were used as reference and the ETT vehicle was tested fully loaded. Five measurements were taken and the vehicle was driven 2 km between each measurement. This test was also done with the vehicle in a Swedish 60-ton configuration. The system overestimated the total weight by 1% for the 60-ton vehicle and by 3% for the 90-ton ETT vehicle. In this context (ensuring right axle loading) the precision must be regarded as satisfactory. However the front axle of the truck, equipped with the spring suspension system, showed 11% higher values compared to the reference weights, which is significant. During the test period the police carried out control measurements of axle pressure and gross weight on several occasions at their permanent weighing station outside Piteå. No excess weights were recorded.

## 4.4 Traffic safety

The literature study regarding truck size and traffic safety indicates that the overall effects are positive for the larger trucks, but there seem to be specific problems that might put the larger vehicles at risk in certain environments, like towns [13].

The focus group interviews with drivers of regular heavy trucks revealed many concerns about how longer and heavier vehicles will comply with other road users. However, the drivers of the ETT vehicle did not experience the predicted problems, but the drivers did point out the importance of planning ahead while driving [4].

## Simulator study and field study

When overtaking of 18.75-m vehicles and 30-m ETT vehicles was compared, a small difference was found in the critical timeslot. The timeslot is defined as the time from when the overtaking car has passed the front of the truck until the two lanes start merging into one (on a 2+1-lane road). The results could not be confirmed in the practical field study when comparing 24-m and 30-m logging trucks. The general conclusion from all the safety studies performed by VTI is that more research is needed. The reduction in the number of vehicles due to higher capacity per vehicle is also not to be forgotten. [4]

## 4.5 Road impact

The data collected from the Percostation system showed no differences in impact in the road body when 60-ton trucks and the 90-ton truck passed. Despite the sensitive equipment, passage of the 90-ton truck could not be identified in the data since the pressure per axle is the same as for regular trucks. Consequently, no increased wear on the roads from higher GCW could be observed.

All bridges have their own weight restriction. At the start of our project, the weight restriction on one bridge to be used by the ETT vehicle was insufficient, so the road authorities carried out the necessary reinforcements to the bridge, enabling it to bear the 90-ton ETT truck trailer combination.

# 4.6 Project management

# Experiences from the crisis group

The crisis group convened once. The crisis plan functioned according to plan after a collision between a car and the ETT vehicle. Fortunately the accident was minor with only slight denting. The driver of the car caused the accident by trying to overtake too late. Only two incidents occurred with the ETT vehicle during the three years. In the second incident, our driver avoided a similar accident by making a controlled braking maneuver.

# Experiences from the hauler companies

Experiences from the hauler companies and their drivers were generally very positive. The ETT vehicle was regarded as very agile with low off-tracking. Full braking gave short, straight and fully controlled braking. The drivers felt they could rely on the braking performance. Reversing the combination with three articulation joints requires planning but is definitely feasible [12]. The vehicles were reversed regularly over the three-year period. The transport buyer SCA stated that the ETT vehicle has shown its capability to efficiently transport timber from forest to industry [2].

The larger stacks (ST) field test was hosted by Stora Enso. Since the terrain was hilly and to some extent combined with poor road conditions, the front wheel drive was greatly appreciated. The ST vehicles showed high productivity both in combination and separately. Stora Enso is very pleased with the results and is preparing for an extension of the tests with more vehicles. [14]

# 5. Conclusions

The measured fuel and  $CO_2$  savings were 22% for the ETT combination and 8-15% for the ST vehicles, depending on the type of transport. The project has shown that high-capacity transports can decrease the emissions of carbon dioxide from road transports.

The studies of traffic safety, along with the achievement of vehicle performance targets, have shown that safety has not been compromised. Since the number of vehicles decreases for a given transport, the overall expected effect is increased traffic safety. Extended tests, mainly on narrower, more winding, roads, would reveal whether the ETT vehicle has corresponding traffic safety on these roads.

The road authorities consider the results of the road wear study positive and accept that the load on each axle and axle group has not increased. The roads used have good bearing capacity, but the road authorities would like to see the road impact study extended onto other

road types and in situations where heavier vehicle combinations are driven closely after one another. The bearing capacity of bridges is generally a greater problem than the bearing capacity of roads. Reinforcements are sometimes necessary, but there are parts of the Swedish road network where 90-ton vehicles could be used without reinforcements. The 74-ton vehicles are much less restricted by bridge capacities.

Weight information can be obtained via the air suspension system on the vehicle combination, so full air suspension is strongly recommended.

## 6. Discussion

We have achieved 22% reduction in  $CO_2$  emissions and subsequent results from measurements with lifted axles show that emissions could be reduced even more. We have focused on energy efficient transport solutions – the energy needed to perform a regular timber transport corresponds to about 1% of the energy in the loaded timber over a transport distance of 100 km. We are showing solutions that will reduce energy consumption.

Since the decision was taken to develop a modular system for forest transports, the process has evolved relatively quickly. Just 18 months after the formation of the project partnership we had the first demonstration rig running. The partnership contained the necessary knowhow and contact network.

The road authorities are investigating whether to allow high-capacity vehicles on a wider network in Sweden 2017, and have requested further research.

## Extended project in process

The overall results from the ETT project are positive and demonstrate great potential, but they also show that further research is needed in several areas. Overtaking is only one of many aspects of traffic safety that needs further investigation. In order to relate the figures of fuel savings and efficiency of the vehicle, more studies are needed in different geographical areas and on different road conditions.

A new, extended project has therefore been set up. The aim is to consolidate research in the field of HCV for transportation of forest products, but also to allow the public and authorities to view HCV in operation, closer to their own region. The new project is called ETTdemo and will, if permitted by Swedish Transport Agency, include a number of HCV studies geographically spread throughout Sweden.

New focus areas are:

- Logistics including truck and train transport in combination how does HCV affect the overall logistic chain?
- Transport of forest fuel as chips demanding a different type of vehicle and a different logistic chain.
- Direct transport from forest landing to industry how does HCV apply to the public and private forest road network?
- How does HCV affect the traffic situation in densely populated regions and how does the general public react to HCV?

- Extended study of traffic safety in different traffic environments. More aspects will be included, in addition to the study on overtaking.

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