DUO TRAILER AN INNOVATIVE TRANSPORT SOLUTION CO-OPTIMIZING MULTI VEHICLE COMBINATIONS

Lennart Cider
Volvo GTT, Sweden
M.Sc. and Ph.D. in Chemical Engineering at Chalmers University of Technology
Currently Project manager, Analysis of High Capacity Transport Vehicle combinations

Heléne Jarlsson
ÅF Industry, Sweden
B. Sc. in Mechanical Engineering at Chalmers University of Technology
Currently Project manager DUO-trailer, design engineering.

Lena Larsson
Volvo GTT, Sweden
M.Sc. in Mechanical Engineering at Chalmers University of Technology and MBA at Gothenburg University
Currently Project manager, High Capacity Transport Vehicle combinations

Abstract

Over the last decade trials with High Capacity Transport (HCT) combinations have been carried out in Sweden. The driving force for these trials has been reduction of CO_2 emissions, increased utilization of the infrastructure as well as transport efficiency. The allowed Total weight has been up to 90 tonnes and the overall combination length has been between up to 32 m, targeting 34 m. The first HCT combination in Sweden was the ETT-combination ("En Trave Till" - One Pile More); results were presented at the HVTT14 conference.

This report covers the vehicle combination DUO-trailer (tractor + semi-trailer + dolly + semi-trailer), field test started in February 2012, Gothenburg to Malmoe with general cargo. The gross combination weight in use is between 35 and 80 ton. Swedish transport regulation allow lifting of axles, this gives possibilities for lower fuel consumption and tire wear as well as better traction and maneuverability for various load cases.

A three axle tractor manages variations in cargo weight and cargo centre of gravity much better than compared to a two axle tractor.

The 6x4 Tractor is preferred over a 6x2 Tractor. A 6x2 tractor has less load on the driven axle compared to the 6x4, but can be used up to around 60 tonnes. A 4x2 tractor is not suitable for a DUO-trailer combination.

Specific fuel consumption is reduced with around 25%, compared to a 6x2 tractor with a single trailer.

Keywords: High Capacity Transport, Sweden, DUO-trailer, A-double, Traction, Fuel consumption, load distribution, weather dependency, Heavy Vehicle Truck Technology, Technical Research.

1. INTRODUCTION

High Capacity Transport (HCT) is a way to reduce emissions from road transport and increase the transport efficiency. In Europe there are various hurdles to overcome; public acceptance, rules and legislation. In our study we work with requirements both theoretically on test tracks and in field test.

HCT in Sweden can be divided in several ways, one is load density and another is load distribution. In our case with the DUO-trailer where general cargo is transported the load is volume limited and mostly front loaded.

The first official HCT combination in Sweden was the ETT-combination ("En Trave Till" - One Pile More). This test started in January 2009 and the results were presented at the HVTT12 (Lofroth, 2012) and the HVTT14 (Larsson, 2016) conferences. This is a typical case where the vehicle combination primarily is weight limited, with an evenly distributed load.

When we started this project in 2010 it was important that all units could be reused in DB Schenker's ordinary fleet. The DUO-trailer layout has been chosen based on modules defined in EC96/53. A single regulation from the Swedish Transport Agency has limited the field test to these modules.

Parallel projects in Finland have tested vehicle combination with longer wheel bases, full trailer instead of dolly and semi-trailer, various tow member positions and steerable last axle on trailer units. Finland will allow vehicles up to 34.5 m later in 2018.

Our DUO-trailer use single mounted tires on all trailing units. In Finland there is a demand to have double mounted tires on 65% of the trailer axles for vehicle combination with Gross Combination Weight (GCW) above 68 tonnes. This will be adjusted for longer combinations with more axles.

During the past seven years the project have focused testing on proving ground and follow up on the field test on fuel consumption, performance and drive ability with the DUO-trailer. This report has a large focus on weight on driven axles.

2. METHOD

2.1 Project Partners

The project contains of several companies and is partly financed by the Swedish government through FFI as seen in Figure 2.1.1.

Figure 2.1.1 - Project partner in the DUO^2 projekt

2.2 Vehicle Combinations

The vehicle combination is designed to maximize volume with modules defined in EC96/53, 13.6 m load carrier length. The internal height in the semi-trailer is maximized to utilize the Swedish free height of 4.5 m and the mega trailer coupling height of 1 m. A three axle tractor with low coupling height is required.

The position of the towing member on the first semi-trailer is a compromise between dynamic stability and swept area at low velocity maneuvering. Measurements and tire configuration are shown in Figure 2.2.1. To minimize fuel consumption the combination has single mounted tires on all axles except on driven axles.

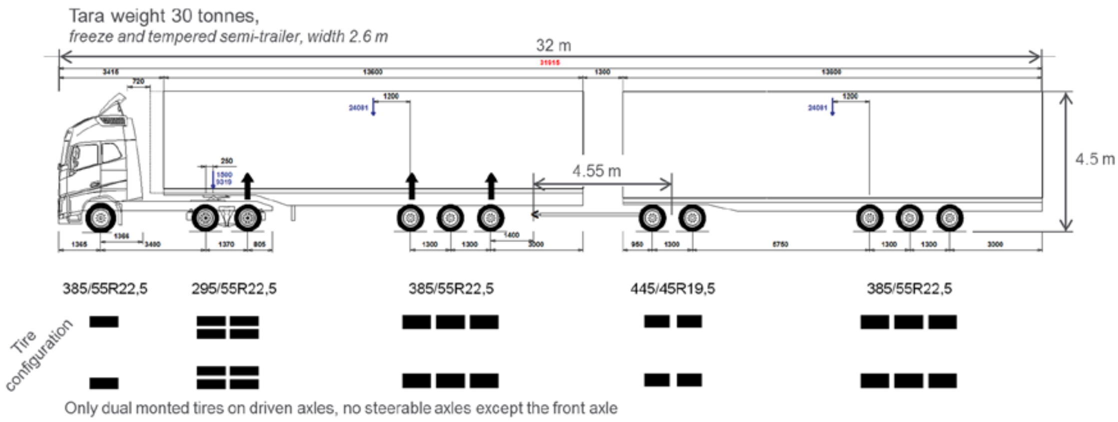


Figure 2.2.1 - DUO-trailer combination layout

Due to the fact that there is more than two units, the complete vehicle combination is equipped with electric/pneumatic brakes and every unit is equipped with an Electronic Braking System (EBS) router. This is to minimize the delay of the braking signal.

2.3 Test Site

The DUO-trailer test is carried out between DB Schenker terminals in Gothenburg and Malmoe, a 285 km long motorway route along the E6, see Figure 2.3.1

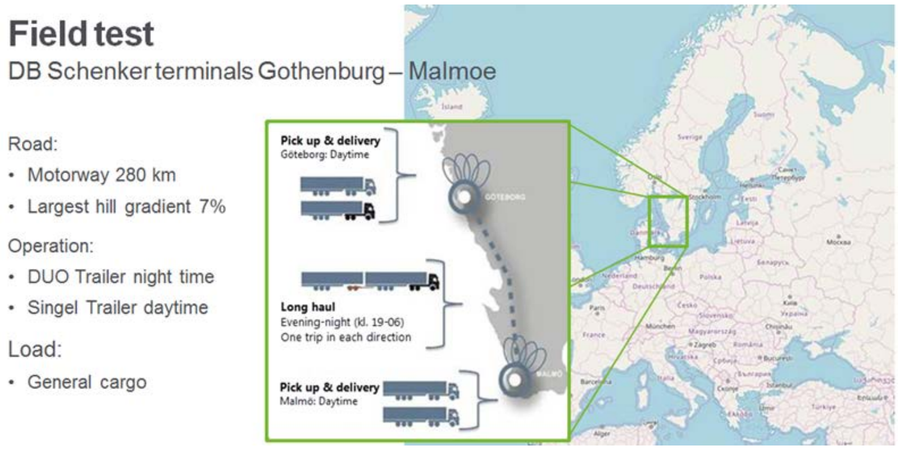


Figure 2.3.1 - Field test route, Motorway Gothenburg – Malmoe

Topography

A hill between Gothenburg and Malmoe has one demanding slope. The height of the hill is merely 200 meter but the slope is 7% which causes problems for all traffic, and especially for trucks. Traction is crucial for a safe passing. The topography is presented in Figure 2.3.2.

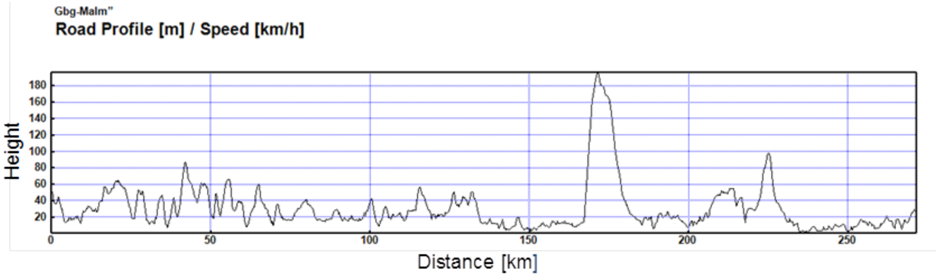


Figure 2.3.2 - Topography of the field test route

Vehicle Units in the Project

The logistics of the field test is based on the use of two trucks, four semi-trailers and one dolly as seen in Figure 2.3.3. With this constellation the DUO-trailer drives from Gothenburg and switch the semi-trailers in Malmoe and returns to Gothenburg. The second truck is stationed in Malmoe for pick-up and delivery.

There are three generations of trucks in the project. The first truck, which is a 6x4 Euro5 truck with a 750 hp engine, is used as a spare truck since early 2017. In this report it will be referred to as Tractor A. The second generation is about the same as the first but is a 6x4 Euro6 truck with a longer wheelbase. The longer wheelbase was a reference for the new/updated bridge formula in Sweden which will come in force in July 2018. This truck is referred to as Tractor B. The third generation is a 6x2 with 540hp engine. This is referred to as Tractor C.

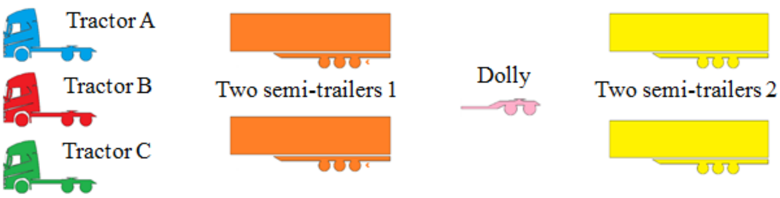


Figure 2.3.3 - Vehicle units in the project

2.4 Fuel Consumption Calculations

We have chosen to calculate both fuel consumption and specific fuel consumption. Let us take the distance D = 285 km from A to B. Typical fuel volume used is V = 150 liters. This gives a fuel consumption of 53 liter/100 km.

The transport is from A to B. The specific fuel consumption, here described as the AB method, takes the full transport cycle into account. In this example the load is M = 32 tonnes. The unit *ml/tonne·km* is used instead of *l/tonne·km* since *ml/tonne·km* gives numbers that are greater than one which is seen in Equation 1.

$$F_{AB} = \frac{V}{M \cdot D} = \frac{150}{32 \cdot 285} \approx 0.016 \left[\frac{l}{tonne \cdot km}\right] = 16 \left[\frac{ml}{tonne \cdot km}\right] \qquad (1)$$

3. RESULTS

3.1 Fuel Consumption

The fuel consumption is recorded for each long haul transport. Typical fuel consumptions are shown in Figure 5.0.1 (page 11).

Specific fuel consumption per load unit is expressed in ml/tonne·km. Tractor C has been tested during a limited period with spring and summer conditions, relatively dry compared to autumn and winter in Sweden. Matching journeys with Tractor A and B has been selected for a more reliable comparison. The comparison is shown in Table 3.1.1.

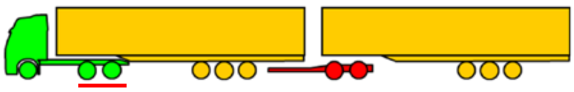
Table 3.1.1 - Typical Spring and Summer fuel consumption for Tractor A, B and C at GCW 62 tonnes

GCW @ 62 tonnes	Distance Km	Volume fuel litre	FC l/100 km	Load tonnes	F_{AB} ml/tonne·km
Tractor A	285	150	53	32	16
Tractor B	285	137	48	32	15
Tractor C	285	130	46	33	14

3.2 Weight Distribution

Weight on every axle has been documented at the start of each long haul trip. In Figure 3.2.1 and Figure 3.2.2 the typical weight distribution is presented. The special regulation for this test allows a GCW up to 80 tonnes. The combination weighs 30 tonnes unloaded; this gives a possibility to load up to 50 tonnes. The weight can be distributed in several different ways. Tractor C has maximum technical total weight of 70 tonnes.

Weight (tonnes)

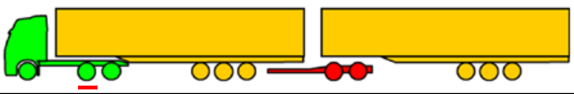


Tractor A&B
(6x4)

	Front	**Drive1**	**Drive2**	Trailer 1	Dolly	Trailer 2	*GCW*	**Driven Axels = Drive 1 & 2**
Unloaded	6	**3**	**3**	7	4	7	*30*	**20%**
Average load	7	**6**	**6**	18	8	12	*57*	**21%**
Fully loaded	7	**8**	**8**	23	16	18	*80*	**20%**

Figure 3.2.1 - Typical Weight Distribution for DUO-trailer with tractor A and B.

Weight (tonnes)



Tractor C
(6x2)

	Front	**Drive**	Tag	Trailer 1	Dolly	Trailer 2	*GCW*	**Driven Axel = Drive**
Unloaded	6	**4**	1	7	4	7	*29*	**14%**
Average load	6	**8**	3	18	8	12	*55*	**15%**
Fully loaded	7	**10**	6	19	14	14	*70*	**14%**

Figure 3.2.2 - Typical Weight Distribution for DUO-trailer with tractor C.

Cargo Centre of Gravity

The DUO-trailer has a large variation in GCW depending on cargo (see Figure 3.2.3). The first semi-trailer is loaded during the day at Pick-Up and Delivery. The second semi-trailer is loaded at the terminal.

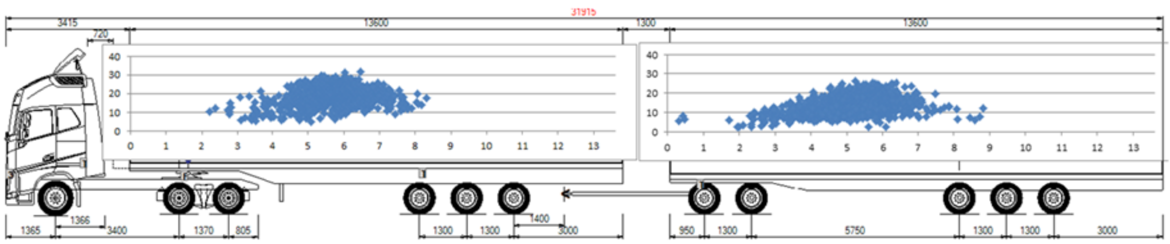


Figure 3.2.3 - Actual load and centre of gravity from 981 transports.

The first trailer varies from 5-32 tonnes and the second from 0 to 28 tonnes. The GCW varies from 35 to 80 tonnes. The centre of gravity (CoG) has a co-variation with the load. The higher the load the more narrow the distribution of CoG as seen in Figure 3.2.3.

Theoretical simulations for a tree axle tractor show about the same weight distribution as seen in Figure 3.2.3 (see Figure 3.2.4).

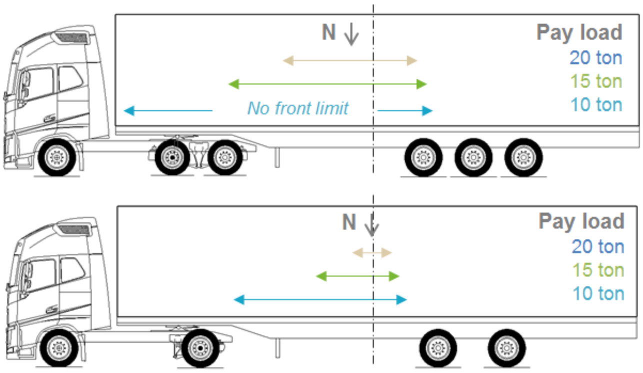


Figure 3.2.4 - Simulated load window/weight distribution of maximum legal rear axle/s weight to minimum 25% of GCW on driven axle for 2 and 3 axle tractor

Weight on Driven Axle/Axles

In Figure 3.2.5, a selected number of comparable trips for the various tractors in DUO-trailer application are shown. Median axle weight on driven axle/axles is 20.6% of the GCW on Tractor B, 21.5% on Tractor A and 13.2% on tractor C.

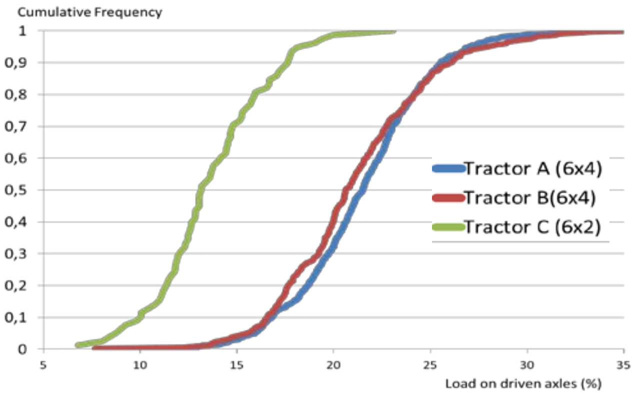


Figure 3.2.5 - Cumulative frequency of weight on driven axles from 1105 transports

In Figure 3.2.6 and Figure 3.2.7 the drive axle load in percentage of GCW is presented. Each cell represents occasions with an actual GCW and a corresponding ratio of load on driven axle. The red box shows that there has been a traction problem during a transport. Wheel spin is much more frequent with Tractor C. A line has been drawn at 20% (requirement in Finland) and one at 25% (requirement in Germany for EMS).

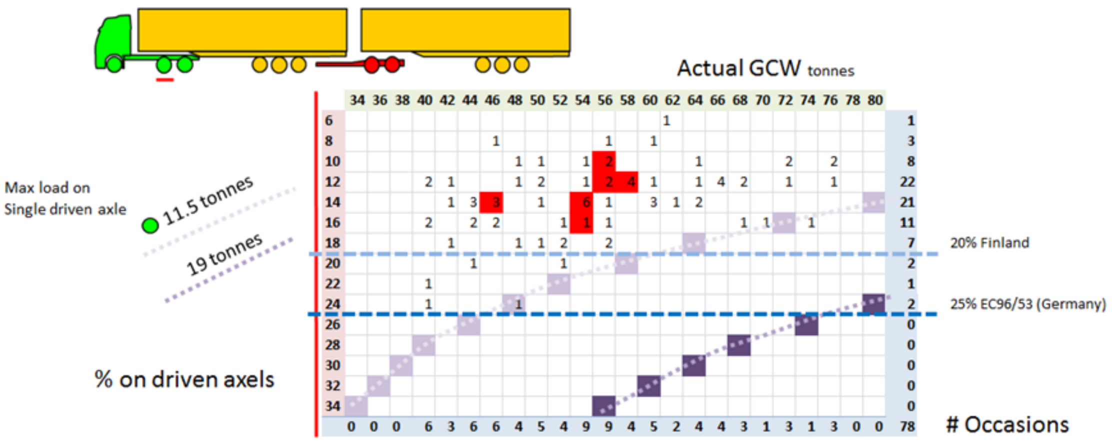


Figure 3.2.6 - Actual load on driven axle for the 6x2 Tractor C from 78 transports. Wheel spin in 8% of the transports (6/78)

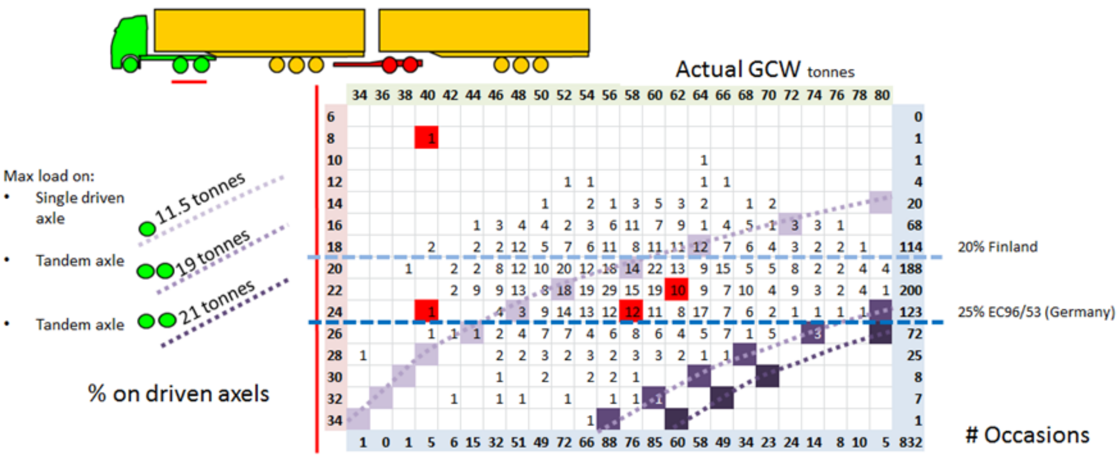


Figure 3.2.7 - Actual load on driven axles for the 6x4 Tractor A&B from 832 transports. Wheel spin in 2.5% of the transports (21/832)

Traction and Weight on Driven Axle/Axles - Hill Climbing

The load on driven axles before and during the hill climbing has been noted at the 7% slope on the field test route.

The first axle on the semi-trailer can either be forced to be lifted, or will automatically be lifted depending on the axle loads. This can increase the load on driven axles with about 1-2 tonnes. The driver can also choose to dump or lift the third axle on the tractor and thereby increase load on driven axle/axles. These weight distribution measures can give up to 5.5 tonnes more on driven axles as seen in Figure 3.2.8.

In the Figure 3.2.8 load transfer is shown with markers. Wheel spin is shown with yellow filled markers. Dotted and dashed lines represent in 130 % of maximum continuous legal weight on driven axles, for 6x2 and 6x4 trucks. Solid lines show the theoretical maximum of transferrable load to driven axle/axles.

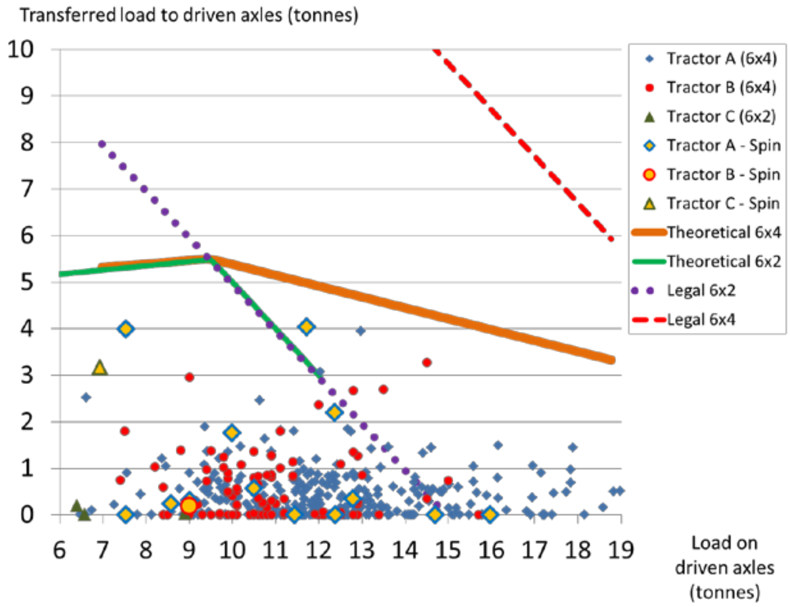


Figure 3.2.8 - Transferred load to driven axles for 412 transports

3.3 Startability and Hill Climbing

Startability has been simulated and tested on proving ground at a friction of 0.8µ which corresponds to dry asphalt. Tractor B (6x4) has a 16 litre engine with 750 hp and the rear axle ratio is 3.09. Simulations indicate that hill start in 12% slope should be fine. The performance of the tractor was tested at proving ground in 2015, with a GCW of 74 tonnes.

Hill start with the inclination of 11.7% was tested successfully with Tractor B. Flat road acceleration resulted in 50 km/h after 30 s (250 m) and 80 km/h in 63 s (850 m). Hill climbing at constant slope of 5% resulted in a top speed of 45 km/h.

In Figure 3.3.2 the vehicle speed at the 7% hill from the field test route is presented. The DUO-trailer had a GCW of 65 tonnes and a lowest velocity of 35 km/h.

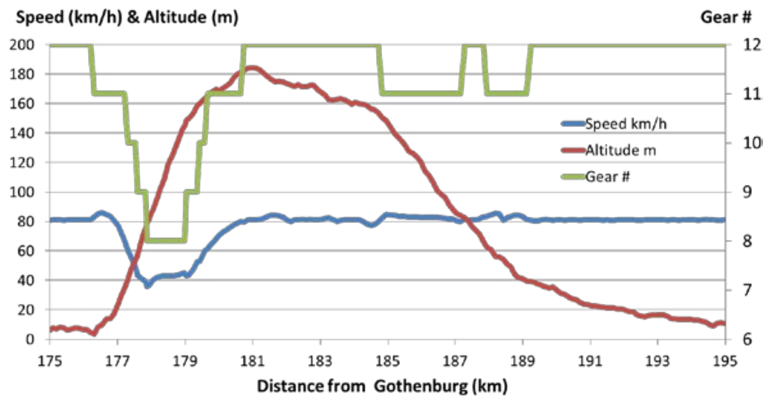


Figure 3.3.2 - Vehicle speed, altitude and gear over a 7% hill, Tractor B

3.4 Braking

Braking distance at straight-line panic braking on slightly wet road surface for various velocities, with Tractor B, loaded to 74 tonnes, is listed in Table 3.4.1.

Table 3.4.1 - Straight-line panic braking, Tractor B. The road surface was slightly wet

Speed	50 km/h	60 km/h	70 km/h	80 km/h	90 km/h
Stopping distance	16 m	25 m	31 m	43 m	56 m

The directional stability at the straight-line panic braking was easily controlled by the driver at all speeds. Panic braking was also tested in a curve at 70 km/h. The stopping distance was not measured, only the directional stability was observed. The directional stability was good and easily controlled by the driver.

3.5 Lane Change and Course Stability

Dynamic stability of the DUO-trailer is addressed in a type vehicle report (Larsson, 2018). The perceived stability with Tractor B from proving ground with GCW of 74 tonnes is good. Lane changes on flat road surface were performed at a speed 70 km/h with duration of 10 s (normal lane change) and with duration of 3 s (rapid lane change). Both manoeuvres were well controllable without any visible tail swing of the last trailer. Course stability assessment on uneven country road (Hällered proving ground, Handling track 2): The combination stayed well in its lane despite of large side dips in the road.

Examples of simulations are lane change amplification of acceleration, rearward amplification of yaw-rate and damping. The three tractors were compared in a 3D simulation. The results are show in Table 3.5.1.

Table 3.5.1 – 3D Simulation of rearward amplification of acceleration, yaw-rate and damping in single lane change ISO 14791 with DUO-Trailer GCW 74 tonnes

	Tractor A 6x4 WB 3.0 m	Tractor B 6x4 WB 3.4 m	Tractor C 6x2 tag WB 3.0 m
Rearward amplification of acceleration	2.09	2.03	2.03
Rearward amplification of yaw-rate	1.87	1.90	1.83
Yaw damping	0.35	0.35	0.36

4. DISCUSSION

The driveability of the DUO-trailer is a prioritized subject. When Tractor C (6x2) was tested we noticed how hard it was to get sufficient drive axle load. This has caused a lot of wheel spin on Tractor C. The drivers have shown their concern regarding driving with the 6x2 tractor at winter conditions. During the tests we have come to the conclusion that a minimum load of 20 % in GCW on driven axles is needed for good driveability. Looking at the drive axle load for Tractor C, we have very few trips that are loaded with respect of drive axle load.

The rearward amplification of acceleration, rearward amplification of yaw-rate and yaw damping are quite similar for the three tractors. All of them show good vehicle dynamic performance.

The first two trucks were 6x4 tractors with D16 750 hp engine. These trucks have been driven in the project without any greater traction problems. There have been some wheel spins in the winter with icy and wet road surface.

In Germany there is a demand for 25% on EMS vehicles and in Finland the demand is 20% of GCW on driven axles. Finland has a maximum bogie load of 21 tonnes on two driven axles. The consequence of a demand like this in Sweden (our maximum bogie load is 19 tonnes on two driven axles) will be that two driven axles are required to drive a DUO-trailer with GCW above 58 tonnes.

In Finland there is also a demand that the weight maximum GCW on the trailer units should not exceed 2.5 times the truck's Gross Vehicle Weight (GVW). This would if applied in Sweden have the GCW for the DUO-trailer listed in Table 4.0.1, depending on the truck wheel base.

Table 4.0.1 - Maximum allowed GCW with demand of 3.5 times GVW

Minimum tractor axle distance* {m}	2.6	4.7
Three Axle Tractor GVW {tonnes}	24	26
DUO-trailer GCW {tonnes}	84	91

*Distance between the front and the last axle on the tractor

Regarding dynamic stability and accessibility the three tractors (A, B and C), are about equal. The stability is found sufficient.

Looking at the specific fuel consumption we can see a great possibility to reduce CO_2 emissions by towing two semi-trailers instead of one.

5. CONCLUSION

A DUO-trailer combination with a 6x4 tractor is a very well-functioning combination. A lift and declutch-able second driven axle is preferred, as well as lift-able and steerable axles on the semitrailers. With this combination we can manage large fluctuations, both in load density and horizontal load centre of gravity.

A 6x2 tractor has less load on driven axle compared to the 6x4, but can be used up to around 60 tonnes. A 4x2 tractor is not suitable for a DUO-trailer combination.

Specific fuel consumption is reduced with around 25%, compared to a 6x2 tractor with a single trailer. Fuel consumption and savings in specific fuel consumption are shown in Figure 5.0.1.

For effective use of DUO-trailer combinations, the same amount of tractors and dollies are recommended. This will take away stress from the long haul drivers.

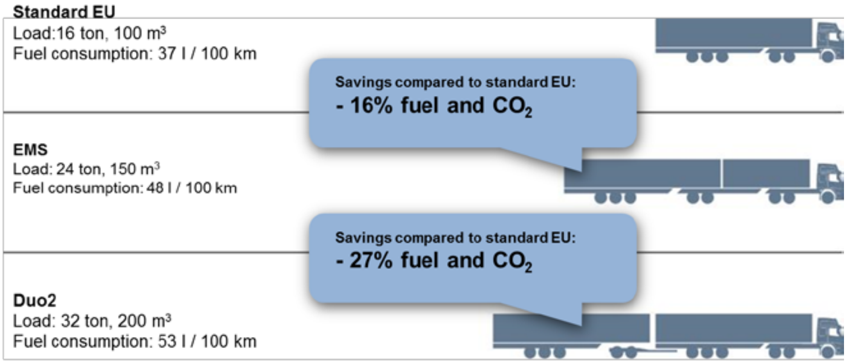


Figure 5.0.1 - Typical fuel consumptions and fuel savings for DUO-trailer, EMS combination and a standard EU combination.

6. REFERENCES

- Lofroth, C., Larsson, L., Enstrom, J., Cider, L., Svenson, G., Aurell, J., Johansson, A. and Asp, T., (2012), “ETT – A Modular System for Forest Transport A three-year roundwood haulage test in Sweden”, HVTT12
- Larsson, L., Cider, L. and Pettersson, E., (2016), “CO-optimizing multi vehicle combinations, fuel consumption & traction in slippery condition”, HVTT14
- Larsson, L., Pettersson, E. and Fröjd, N., (2018), “Type Vehicle Combinations - HCT Sweden 25.25 To 34 meters”, HVTT15

7. ABBREVIATIONS & NOMENCLATURE

CO_2	Carbon Dioxide (global warming greenhouse gas)
CoG	Centre of Gravity for the Cargo in a semi-trailer
D	Distance travelled loaded
Dolly	 Trailer with only a fifth wheel
DUO-trailer	Tractor + Semi-trailer + Dolly + Semi-trailer
EBS	Electronic Braking System
EMS	European Modular System
ETT	En Trave Till - One Pile More
EC96/53	Maximum authorized weights & dimensions in national and international traffic within the European Community
F_{AB}	Specific Fuel Consumption *{ml/tonne·km}*
FFI	Strategic Vehicle Research and Innovation – (Swedish program)
GCW	Gross Combination Weight
GTT	Group Truck Technology
GVW	Gross Vehicle Weight
HCT	High Capacity Transport
HVTT	Heavy Vehicle Transport Technology
litre	1/1000 m^3
m	The meter is defined to be the distance light travels through a vacuum in exactly 1/299792458 seconds
M	Mass of goods transported {metric tonne=1000 kg}
NVF	Nordic Road Association (nordiskt vägforum)
Semi-trailer	 Trailer without front axles
tonne	1000 kg
Tractor A	Tractor 6x4, Short WB, 750 hp (552 kW)
Tractor B	Tractor 6x4, Longer WB (+4 dm), 750 hp (552 kW)
Tractor C	Tractor 6x2, Short WB, 540 hp (397 kW)
V	Volume of fuel consumed when loaded
WB	Wheel Base Distance between front axle and first driven axle
ÅF	ÅF is an engineering and consulting company with assignments in the energy, industrial and infrastructure sectors.