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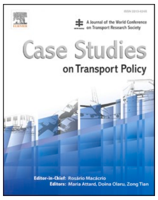

Environmental and economic potential of high-capacity trucks

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ABSTRACT

High-capacity trucks (HCTs) are vehicles that are heavier or larger than normally allowed and are used as a means of increasing the efficiency of road freight transport and reducing emissions. The present research analyses the economic and environmental efficiency of HCTs by comparing them with normal semitrailers. Survey-based estimates on cost structure, fuel consumption, load factor and empty running of semitrailers, road trains and HCT combinations currently operating in Finland have been used to calculate whether HCTs improve the cost competitiveness and reduce the emissions of road transport. The results indicate that HCTs have a 42% emission reduction potential in mass-based transport and a 38% potential in volume-based transport compared to normal semitrailers.

1. Introduction

The world's annual CO_2 emissions reach 50 billion tonnes, of which around 16 % is associated with transport (Climate Watch, 2022). Of these emissions, around 11 %-points is caused by road transport, of which roughly 60 % in passenger and 40 % in freight transport (IEA, 2022). Thus, road freight transport corresponds to 5–6 % of all global CO_2 emissions, or 2.5–3 billion tonnes annually. After aviation, road transport is the second least CO_2 −efficient mode of transport (see, e.g., Luo et al. 2016). Although maritime transport dominates international transport flows, the majority of domestic transport is performed by road transport. In the European Union, around 75 % of freight transport is carried by road.

Considering the high share of road transport and its externalities including e.g. emissions, noise and congestion, the European Union (EU) has initiated policies to reduce the harmful impacts of road transport (see European Commission, 2011). The methods include supporting a modal shift towards more sustainable transport modes as well as tightening the energy efficiency requirements of road transport. However, balancing between the impacts of these policies is a challenge, because increasing the energy efficiency of road transport tends to make it more cost competitive, potentially increasing the share of road transport even more.

At the same time, the nature of road transport makes modal shift away from it difficult. It is commonly known in transport economics that road transport is the most cost efficient and flexible method for transporting cargo over short distances (see, e.g., Rodrique, 2020). After a certain distance (usually 500–700 km), rail transport and, ultimately, sea/inland waterways transport become more cost efficient. This is the main explanation for the dominating role of road transport in Europe: as much as 95 % of road freight transport and transported tonnes travel a distance of less than 500 km (Eurostat, 2021). These flows cannot easily be transferred to alternative transport modes.

This forces policymakers and the transport industry to seek emission reductions within road transport. The means are partly technical, such as Euro emission and energy efficiency norms, along with operative in the form of economical driving by increasing load factor and minimising empty running (Santén, 2017).

Also longer and heavier vehicles (high-capacity trucks; HCTs) have been discussed in the literature and policymaking as a means of improving energy efficiency (see for example ITF, 2019). The rationale is in economies of scale, meaning that the larger the vehicle, the lower the emissions per unit of transport performance.

Currently, the European Union legislation sets EU-wide limits (length, height, weight, etc.) for trucks in international traffic, whereas in national traffic, countries can permit the use of longer and heavier vehicles. Therefore, the definition of a HCT depends on the country and context. Generally, in the EU context, a truck is considered to be a HCT, if it exceeds the 18.75-metre and 40-tonne limits (Sanchez Rodriques et al., 2015). Following this, for example Ortega et al. (2014) and Meers et al. (2016) define HCTs to be 25.25 m long with a maximum weight of 60 tonnes. In some EU countries, such as Sweden and Finland, a 25.25 m long and 60-tonne vehicle is regarded as normal, whereas HCTs can be up to 34 m long (Finland 34.5 m) and weigh 76 tonnes (Pålsson et al.

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2017). In these countries, HCTs have rapidly been adopted to use. Since the introduction of HCTs in domestic road freight transport in Finland in 2013, initially through a limited number of test permits, their market adoption has been rapid. According to Traficom (2022), the share of HCTs of over 68 tonnes in road freight transport work measured in tonne-kms was close to zero in 2013, but had reached 30 % by 2020, while the share of Heavy Goods Vehicles (HGVs) between 64 and 68 tonnes grew from almost zero to almost 20 %. At the same time, the share of HGVs between 54 and 64 tonnes plummeted from approx. 70 % in 2013 to under 30 % in 2020.

Even with their potential benefits, extant empirical research on the energy efficiency of HCTs is limited. For example, Sanchez Rodriques et al. (2015) stated that 'HCT performance assessment is a major problem due to lack of empirical data'. The present research aims to fill this gap by providing survey-based empirical evidence of the environmental and economic efficiency of HCTs. As Finland, along with Sweden is the only country in the European Union to allow for HCTs as large as 34 m or 76 tonnes, it also provides an interesting case example on the impacts of allowing these combinations. Even if road transport market within the European Union is still subject to some national peculiarities, the road transport companies still operate in the joint European market. Therefore, the results of this research provide evidence on the environmental and economic impact, in case similar policies would be adopted in other European countries as well. The analysis is based on data collected in 2023 from 275 road transport firms that operate 5,184 individual trucks.

We compare the energy efficiency of ordinary trailer and road tractor combinations and HCT units by taking into account operational efficiency to estimate both the economic and environmental potential of HCTs. By potential we mean a possible reduction in costs and emissions per unit of transport in case a larger vehicle is used. For clarity, in the current research, a trailer refers to a maximum of 18.75 m and 40-tonne unit, road train to a 25.25 m and 60-tonne combination and HCT to combinations exceeding those limits, i.e. up to 34.5 m and 76 tonnes.

The paper is structured as follows: Chapter 2 introduces the key literature on the environmental and operational efficiency of road freight transport, together with a recap of research on HCTs. Chapter 3 presents the research methodology together with a discussion of validity and reliability. Empirical results are presented in Chapter 4, followed by a discussion and conclusions in Chapters 5 and 6.

2. Theoretical background

2.1. *Environmental impact of road transport*

The IEA (2022) estimates that around 40 % of global emissions from road transport originate from freight transport. In the European Union, the role of passenger road transport is higher, and only around 25 % of road transport emissions originate from freight transport (ICCT, 2021). In addition, transport in general and road transport in particular is one of the few sectors, where emissions are expected to grow in the future, here in the case of stated policies. For example, in the EU, emissions from transport have increased 33 % since 1990, whereas emissions from other sectors have dropped by 32 % during the same period (ICCT, 2021).

The significance of emissions from road transport has also been a focus in the research literature from several perspectives. One of the research streams has been the measurement and development of emissions both at the country level and regionally. At the country level, Piecyk and McKinnon (2010) presented a calculation method for fuel consumption and CO_2 emissions, together with a forecast of the carbon footprint of road transport in the UK in 2020, whereas Hickman and Banister (2007) had a longer time perspective, creating three scenarios of CO_2 emissions in the UK until 2030, emphasising that there will be an increase in overall CO_2 emissions of freight transport, of which the increase will especially be associated with road transport. Eom et al. (2012) took a wider geographic perspective, reporting increased energy usage and CO_2 emissions in 11 IEA countries. Recently, Marrero et al. (2021) estimated the road transport emissions within the EU, and Krause et al. (2020) compiled expert-based scenarios on how emissions would develop until 2050.

In many studies, the increasing amount of emissions from road transport has been associated with an increase of economic activity and transport performance. Andres and Padilla (2015) studied road freight transport in Spain, concluding that the energy efficiency per transported unit improved between 1996 and 2012, but the overall energy consumption increased because of increased activity. Ruzzenenti and Bassosi (2009) came to similar results by estimating the development of energy efficiency in the EU freight transport sector over a period of 30 years, showing improved energy efficiency both per km and tonne-kilometres but also indicating an increase in energy consumption and total emissions because of increased transport volumes.

Because of the increase in transport volumes, attention has been directed given on how to decouple emissions from volume. Tapio (2005) presented empirical evidence from Finland, reporting a reduction in transport performance, energy usage and emissions, despite increasing economic activity, but failing to identify a major structural change of the economy and production. Previously, McKinnon (2007) presented frameworks for emission reduction in road transport, emphasising the potential of operational efficiency. Apart from technical and operational measures, transport emissions have also been considered from a strategic perspective. Pålsson and Kovacs (2014) used a stakeholder perspective, arguing that a reduction of transport emissions is a strategic decision and potentially a source of competitive advantage.

2.2. *Performance measurement of transportation*

Transport performance can be considered from the perspective of an individual load or vehicle or from that of an entire fleet. Also vehicle utilisation, such as the load factor and share of empty running (Léonardi and Baumgartner, 2004), are part of the equation. Similarly, studies in the literature have approached performance from a more traditional transport perspective, whereas other studies have addressed it more widely, i.e. along supply chains.

Even traditional transport literature lists numerous factors affecting performance. Abate (2014) analysed the capacity utilisation in (Danish) road haulage, including the extent of empty running and weight-based load factor, coming up with the result that distance has a positive impact on load factor and the probability of loaded trips (less empty running), whereas the size of the truck has a negative, although not linear, relationship with the load factor. The argument for this was that the choice of load factor depends on two goals: either the carrier aims to optimise the load factor by filling as small vehicle as possible (as hypothesised by Fowkes, 2007) or alternatively tries to avoid the higher opportunity costs of running partially filled larger vehicles. This hypothesis has also been supported by Liimatainen et al. (2012), who found that choosing the vehicle size according to the load was the second highest ranked energy efficiency practice when surveying Finnish road haulage firms.

Arvidsson (2013) studied load factor from the perspective of routing, while also taking the emissions from transport into account, obtaining somewhat counterintuitive results on load factor. According to Arvidsson (2013), the suboptimal routing of distribution may in some cases cause operators to drive longer distances with a higher load factor, hence creating unnecessary emissions. This challenge was highlighted by Dente and Tavasszy (2018), who argued that, unlike what has been commonly stated, emissions are not a linear function of the transport distance but more of a dynamic equation that includes speed and load factor, among other variables. McKinnon and Ge (2006) focused especially on empty running, listing the factors of low potential for backloads (and, therefore, high empty running), including current level of return loading, short average length of empty journey, limited duration of trips and a low density of the transport network, which includes both vehicles and shippers.

García-Arca et al. (2018) attempted to introduce key performance indicators (KPIs) from the world of industrial production into road transport by including a larger variety (12) of KPIs while also including the traditional transport distance, vehicle utilisation and transport costs. Vallejos et al. (2022) considered the role of supply chain integration, arguing that integrating multiple tiers of supply chain into the same transport network reduces empty running by increasing the combined efficiency. Santén (2017) emphasised the role of logistics, suggesting that activities such as packaging efficiency, loading efficiency, booking efficiency, and the flexibility of lead times all tend to increase load factor. From the perspective of environmental impact, however, there is a possibility that the relationship with operational performance is not that straightforward because a so-called rebound effect may take place (see, e.g., Llorca and Jamasb, 2017). This would mean that improving the (energy) efficiency of transport makes it also more cost competitive, hence negating some of the positive effect because it creates an incentive to transport more and longer distances.

Solomon et al. (2019) took a more theoretical approach applying institutional theory and the triple bottom line of sustainability by considering the traditional measures of transport performance as originating from economic (institutional) pressures, while acknowledging they have an environmental aspect as well. Along both the economic and environmental dimensions of sustainability, the social aspect of enhanced safety should also be considered in the HCT discussion.

2.3. *High-capacity trucks*

A HCT refers to a commercial vehicle with a cargo-carrying capacity that exceeds the normal capacity of a heavy goods vehicle (Monios and Bergqvist, 2017). To some extent, it is used interchangeably with longer and heavier vehicles (LHVs), referring to the fact that the additional capacity is achieved by expanding the length of the maximum allowed weight of the vehicle. However, in some cases, it is possible to expand the maximum cargo carrying capacity by technically modifying the cargo space (see, e.g., Palmer et al., 2018). For this reason, a HCT can be considered a more correct term.

The definition of a HCT is still difficult to define because, within the EU, the maximum allowed lengths and weights of heavy goods vehicles differ. At the European level, the overall accepted measures are 18.75 m length and a maximum weight of 40 tonnes (ITF, 2021). However, under current EU regulation, countries can allow LHVs in their national traffic (European Commission, 1996). Therefore, there are country-level differences in what is considered a HCT. In the Netherlands, a HCT is 25.25 m long with a maximum allowed weight of 60 tonnes. In Sweden, the permissible maximum weight in limited parts of the road network is 76 tonnes, whereas in Finland, the maximum allowed length is 34.5 m and permissible maximum weight 76 tonnes (OECD, 2021).

These differences also have to be kept in mind when discussing the literature on HCTs: most studies have considered a HCT to be 25.25 m long with a maximum weight of 60 tonnes, as is the case in the Netherlands. The potential of such HCTs has been estimated in different parts of Europe. Ortega et al. (2014) simulated the potential implementation of HCTs in Spain using 25.25 m/60 t as a comparison, whereas Lindt et al. (2020) estimated the environmental and cost impact of longer and heavier vehicles (comparing 25 m and 60-tonne vehicles with 18.5 m and 40-tonne vehicles) on the Lidl distribution network, ending up with 15 % emission and 30 % cost savings on average. Sanchez Rodrigues et al. (2015) estimated the potential of adopting HCTs in Germany from a cost-benefit analysis, considering operational performance such as load factors, empty running and so forth by interviewing and surveying (27) road haulage firms in Germany.

Because HCTs are expected to impact the cost competitiveness of road transport, Meers et al. (2016) calculated the possible effects of LHV vehicles (25.25 m and 60 tonnes) compared with the common 18.75 and 40–44 tonne vehicles, especially from the perspective of a reverse modal shift in intermodal transportation.

Previous pieces of research considered HCTs as being 25.25 m/60 t. However, in Sweden and Finland, the current regulations allow for even larger vehicles. Based on telemetric data, Hassan and Helo (2020) presented a case study of an individual company operating in the Finnish market that considered both the revenue potential and estimated cost, concluding that the size advantage of HCT would result in moderately higher revenue potential and profitability. Berqvist and Behrends (2011) assessed the (economic) effects of longer vehicles in a Scandinavian setup, especially from the perspective of pre- and post- haulage, identifying cost savings potential and conditions to meet the savings, whereas Pålsson et al. (2017) estimated the impact of longer and heavier road vehicles in Sweden, creating scenarios and estimating modal shift and its impact for HGVs up to 76 tonnes and 34 m, suggesting policy measures to prevent a modal shift.

There has also been some research regarding the safety of HCTs. One of the usual arguments against HCTs is that their size and weight would have a negative impact on road safety, so they should not be allowed. Although this might be intuitively correct, because a larger weight could especially be considered to have a more significant impact in case of an accident, previous research has been unable to find any significant connection between the size of the vehicle and road safety. For example, Castillo-Manzano et al. (2021) estimated the impact of megatrucks (25 m, 60 tonnes) on road safety but were unable to detect any significant impact.

3. Methodology and data

The empirical data were collected as part of a biannual nationwide Finland State of Logistics survey in 2023. The multitheme survey has three major target groups: manufacturing and trading firms as users of logistics services and logistics service providers, of which the vast majority are road haulage firms.

The survey was sent to 4,002 road haulage firms in cooperation with the Finnish Transport and Logistics Association (the association of Finnish road haulage firms). 224 complete and usable responses were received, resulting in a response rate of 5.1 % of the road haulage sample.

The Finnish road transport industry comprises a large number of small firms, so the response rate underestimates the representativeness of the sample, which included many, if not most, of the larger road haulage firms. The combined turnover in the sample represented around 40 % of the turnover of road haulage in Finland.

The survey questions included basic data of the company, such as turnover and the main goods categories transported. The respondents were also asked to provide the number of vehicles in different vehicle categories (semitrailer combinations, road trains and HCT combinations) classified according to current Finnish definitions. As presented in Fig. 1, in this research a semitrailer refers to a vehicle that has a maximum length of 16.5 m and a maximum weight of 40 tonnes. A road train in national traffic has a maximum length of 25.25 m and maximum weight of 60 tonnes, whereas a HCT combination has a maximum length of 34.5 m and maximum weight of 76 tonnes. Considering the connection between weight, it is possible that already a smaller vehicle can be considered as a HCT, as especially in mass-based transports the weight of the vehicle may be high also with shorter vehicles.

To be able to estimate the cost effectiveness of different vehicle combinations, respondents were asked to estimate the share of the following cost components as the share of total costs (100 %):

- Driver's salary
- Fuel
- Repair and maintenance
- Tyres
- Insurance
- Capital costs

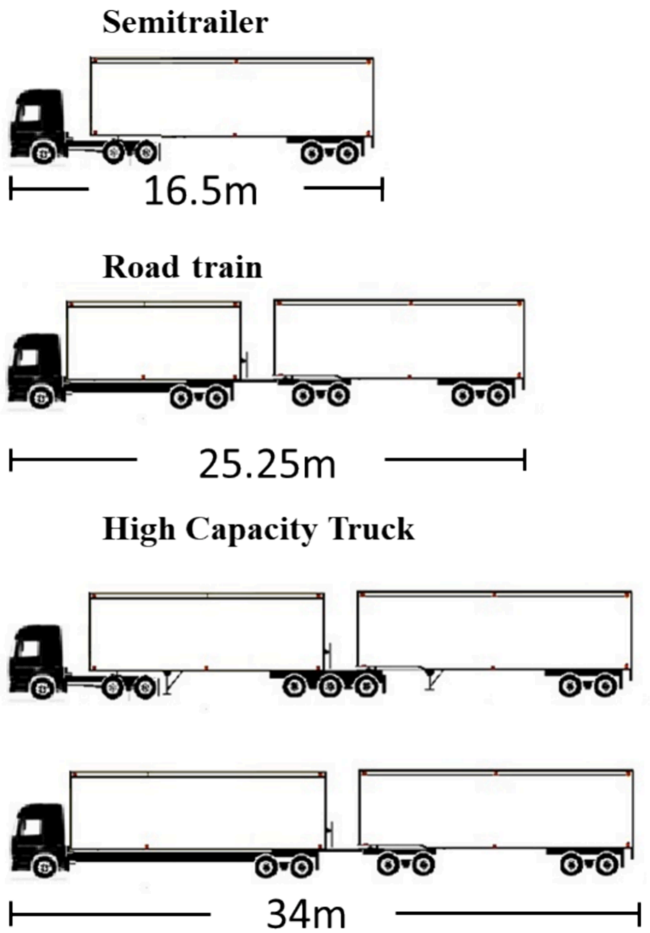

Fig. 1. Graphical illustration of maximum lengths of heavy goods vehicle combinations included.

- Administration

In addition, the respondents were asked to estimate the average fuel consumption per 100 km for the different vehicle combinations. Based on these and statistical data on diesel prices in Finland at the time of the survey, the total cost and cost per 100 km was calculated for the vehicle types. Fuel prices have been highly volatile due to e.g. the COVID-19 pandemic followed by Russia's aggression in Ukraine and the resulting disturbances in the energy market. For these reasons, fuel costs (and division) were updated by assuming that the fuel cost would react with the fuel price, whereas the other cost components would remain at their initial (€/100 km) level.

The operational efficiency of the different vehicle types was also taken into account. The respondents were asked to provide estimates on their average load factor (when transporting cargo) as a percentage of total cargo carrying capacity, as well as the percentage share of empty running of their transport performance.

The data were analysed with three regression models (Equation (1), with fuel consumption, load factor and empty running as the dependent variables and vehicle type (Vehicle) and cargo type (Cargo) divided into mass and volume cargo as categorical independent variables. With categorical independent variables, the regression analysis estimates whether the intercepts of the categories are statistically significantly different. In case they are, the coefficient of the category indicates the difference to the reference category. The vehicle type included three categories, semitrailer, road train and HCT as a reference category. Cargo type was divided to mass- and volume –based. Because it is possible that the fuel consumption and operational efficiency would be different for different vehicle categories in different cargo types, the interaction term to account for this was also included in the model:

$$Dependent = \beta_0 + \sum_{i=1}^{3} \beta_1 Vehicle_i + \sum_{J=1}^{2} \beta_2 Cargo_j + \sum_{i=1}^{3} \times \sum_{j=1}^{2} \beta_3 Vehicle_i {*} Cargo_j + e_i \qquad (1)$$

The variables were tested for the basic assumptions of linear regression (Montgomery et al., 2021), including multivariate normality, multicollinearity, autocorrelation and homoscedasticity. Based on the Breusch–Pagan test (Breusch and Pagan, 1979), heteroscedasticity was detected. To account for heteroscedasticity, the analysis was performed as a weighted least squares (WLS) regression, following Neter et al. (1996).

The estimated coefficients of a normal OLS provide a regression equation that minimizes SSE=$\sum e_i^2$, whereas a WLS regression weights the individual observations to counterbalance non-constant variance. For an OLS regression analysis, the equation for the sum of square of the residuals is:

$$\sum e_i^2 = \sum (y_i - \alpha - \beta x_i)^2 \qquad (2)$$

For a WLS regression, however, the sum of square of residuals can be written as:

$$\sum w_i e_i^2 = \sum w_i (y_i - \alpha - \beta x_i)^2 \qquad (3)$$

In this case, the weights were created by running an auxiliary regression using absolute residuals as dependent and original predictors as independents to calculate smoothed standard deviations. Thus, the weights used in the WLS were $w_i = 1/(\hat{s}_i)^2$.

The results were then used to estimate the cost and emissions efficiency of different HGV combinations.

4. Results

Table 1 presents the descriptive statistics of the analysed sample. 77 firms reported data on semitrailers, 154 on road trains and 44 on HCTs. This brings the total number of vehicle-firm observations to 275. As the sample comprised of 224 individual firms, it is obvious that 51 of them utilize multiple vehicle types. As the unit of analysis is the vehicle, these were treated as individual observations. Combined, these firms operated a total of 5,184 vehicle combinations, of which there were 1,738 semitrailers, 2,435 road trains and 1,011 HCT combinations.

The respondents were also requested to report their main cargo type to determine the nature of their transport operations. This was used to categorise whether the transports of the company (and associated with the vehicle) were limited by the mass or volume of the transported good. This was done to get a more precise picture of the fuel consumption of the vehicles because basic physics dictate that additional weight increases fuel consumption. Theoretically, this could be calculated precisely, whereas, in practice, the relationship depends on operational factors as well.

Of the transported goods, food and food products, parcel distribution, unit cargo and interchangeable platforms were classified as volume-based cargo. International transports were also classified into this category, because road transports to and from Finland consist mainly of high valued and thus voluminous rather than heavy goods. (Table 1).

Rock, gravel, sand, other dry bulk, liquid bulk and raw timber were classified as mass-based transports. Of the 5,184 vehicles, 4,504 were operating in volume-based transports and the remaining 680 in mass-based transports. (Table 1).

Table 2 presents the cost structures of the three analysed vehicle types. Drivers' salaries were the highest individual cost component, varying between 34.5 % (semitrailers) and 33.1 % (HCTs). Fuel costs

Table 1
Descriptive statistics of the survey sample.

	Number of companies Semitrailer	Road train	HCT	Total	Number of vehicles Semitrailer	Road train	HCT	Total
Volume based transports								
Food and food products	8	28	13	49	49	187	122	358
Parcel distribution	1	6	1	8	5	25	2	32
Unit cargo	28	39	16	83	416	1495	595	2506
International transports	11	4	3	18	1081	314	192	1587
Interchangable platforms		7		7		21		21
Mass based transports								
Rock, gravel, sand etc.	5	14	1	20	10	50	1	61
Other dry bulk	12	19	6	37	89	139	70	298
Transport of liquid bulk	3	9		12	5	56		61
Raw timber	2	21	1	24	6	86	1	93
Other	7	7	3	17	77	62	28	167
	77	**154**	**44**	**275**	**1738**	**2435**	**1011**	**5184**

Table 2
Cost structure and operational performance of the studied vehicle types.

	Semitrailer Average	std.	Road train Average	std.	HCT Average	std.
Driverśsalary	34.5 %	9.696	34.1 %	9.268	33.1 %	11.185
Fuel	31.7 %	5.765	29.4 %	6.438	27.9 %	5.047
Repair and maintenance	9.0 %	3.43	9.1 %	2.839	8.8 %	2.186
Tyres	5.0 %	3.036	5.5 %	3.308	6.3 %	3.237
Insurance	5.2 %	4.586	4.8 %	2.382	5.7 %	3.595
Capital costs	9.1 %	3.895	10.3 %	4.078	10.6 %	2.371
Administration	5.5 %	4.493	6.7 %	6.25	7.6 %	6.034
Total	100 %		100 %		100 %	

were the second largest cost component in all vehicle types. For semitrailers, fuel costs accounted for 31.7 % of total costs, 29.4 % for road trains, and 27.9 % for HCT combinations, respectively.

Table 3 presents the results of the regression analysis. Considering fuel consumption, vehicle type and cargo type were both significant. HCTs had an average consumption of 50.4 L per 100 km. Semitrailers consume 14.16 L less fuel per 100 km than HCTs, and the difference was found to be statistically significant. The difference (0.764 l/100 km) in fuel consumption between road trains and HCT was not statistically significant. Mass-based transports had, on average, 4.9 L higher consumption per 100 km compared with volume-based transports. The interaction term measuring the joint impact of vehicle type and cargo type was also found to be statistically significant. Regarding fuel consumption this means that the impact of vehicle type on fuel consumption was different on volume-based transports compared to mass-based transports. The negative coefficient indicates that in volume transport, increasing the size of the vehicle increases fuel consumption less than in mass-based transport.

Load factor and empty running were measured as percentages (min. 0 %, max. 100 %). Vehicle and cargo type were also mattered when considering load factor and empty running. HCTs had a higher load factor than road trains (−7.3 %) and semitrailers (−12.67 %). There were no statistically significant differences in load factors between vehicle types, whereas on average, the vehicles in mass-based transport were operating with a 7.2 % lower load factor.

The differences in the share of empty running were significant. HCTs had on average 29.4 % empty running, whereas semitrailers did, on average, have 3.9 %-points less and road trains 6.5 %-points more empty running than HCT combinations. The main explanatory factor was the division between volume-based and mass-based transports: on average, mass-based transporters reported 14.1 % more empty running. Also the interaction term was found to be significant. More precisely, it would seem that the size of the vehicle has more impact on empty running in volume-based transport than in mass-based transport.

Table 4 presents the cost levels per component and total cost per 100

Table 4
Cost structure (€/100 km) of different vehicle types.

	Semitrailer	Road train	HCT
Driveŕs salary	58.8	84,0	88,7
Fuel	62.5	92,3	103,9
Repair and maintenance	15.3	22,3	23,5
Tyres	8.6	13,6	16,8
Insurance	8.8	11,9	15,1
Capital cost	15.4	25,5	28,4
Administration	9.4	16,7	20,4
€/100 km	178.8	266.3	296.9
€/km	1.8	2.7	3.0
€/m^3/km	0.018	0.017	0.015
€/ton-km	0.07163	0.07212	0.05716
Fuel cost €/m3/km	0.00620	0.00586	0.00541
Fuel cost €/ton-km	0.02502	0.02500	0.02001

Table 3
Results of the regression analysis.

Dependent Variable	**Fuel consumption**			**Load factor**			**Empty running**		
	B	Std. Error	t	B	Std. Error	t	B	Std. Error	t
Intercept	50.4**	0.682	73,906	93.775**	1.036	90.559	29.420**	1.342	21.93
Vehicle = 1 semitrailer	−14.16**	1.398	−10.130	−12.673	2.020	−6.272	−3.933**	1.586	−2.479
Vehicle = 2 road train	0.764	1.038	0.736	−7.332	1.280	−5.729	6.524**	1.483	4.400
Vehicle = 3 HCT (reference)	0a	.		0a	.		0a	.	.
Cargo = 1 vol	−4.99**	0.899	−5.553	−8.073**	1.072	−7.530	−14.024**	1.386	−10.121
Cargo = 2 mass (reference)	0a	.			.		0a	.	.
Vehicle1*Cargo1	−3.22**	1.431	2.250	−7.591**	2.130	3.733	7.682**	1.639	4.686
Vehicle2*Cargo1	−6.873**	1.060	6.486				7.414**	1.537	−4.823
	0a	.		0a	.		0a	.	.
R^2	0.44			0.107			0.206		

** = significant on 0.01 level.

km, derived from the survey-reported cost structures and fuel consumption and the diesel price in Finland in May 2023 (1,5€/l, VAT excluded). In addition to the average costs per vehicle per 100 km, the costs were also calculated per m^3-km and tonne-km. For this purpose, the maximum capacities of semitrailers, road trains and HCT were estimated. The following parameters were used in the calculations: semitrailer, maximum capacity 100 m^3, or 25 tonnes, road train 158 m^3, or 35 tonnes, and HCT 192 m^3, or 52 tonnes.

The total costs of a semitrailer were estimated to be, on average, 178.8€/100 km, whereas the corresponding figures for road trains and HCTs were 266.3€/100 km and 296.9€/100 km, respectively. Surprisingly, the average cost per nominal unit of transport was found to be equal in road trains and semitrailers.

Semitrailers were found to have a higher cost per m^3 than road trains, whereas HCTs were found to be the most cost effective both in terms of tonne-km and m^3-km. This indicates that a larger vehicle is not necessarily more cost effective, but the competitiveness of different vehicle sizes depends on transported cargo and the operational efficiency related to it.

Table 5 expands the analysis to include operational efficiency for fuel consumption and emissions per unit of transport performance. When operational efficiency is taken into account, road trains were more efficient per tonne-km and m^3-km than semitrailers, whereas HCTs were more efficient than the two other vehicle types.

In mass-based transport, on average, HCTs were 33.2 % more fuel efficient than semitrailers and 27.8 % more efficient than road trains. In volume-based transports, HCTs were 34.2 % more fuel efficient than semitrailers and 20.4 % more efficient than road trains. Further, road trains were 17.3 % to 7.4 % more fuel efficient than semitrailers.

5. Conclusions and discussion

The current research has analysed the economic and environmental performance of heavy goods vehicles. By surveying road haulage firms in Finland, we provide estimates on the cost distribution and fuel consumption of three different types of heavy goods vehicles: i) semitrailers that are commonly used in Europe, along with ii) road trains and iii) HCT combinations, which are currently allowed in national traffic in Sweden and Finland.

The performance of HCTs was estimated by taking into account a set of background variables, including cargo type and operational efficiency measured in fill rate and share of empty running.

Table 5
Emission efficiency of different vehicle types.

Fuel consumption		
	Mass	**Volume**
Semitrailer	36.2	33.0
Road train	49.6	42.8
HCT	50.4	45.4
Cargo capacity (gross)		
Semitrailer	25 t	100 m^3
Road train	37 t	157 m^3
HCT	52 t	192 m^3
Average load (based on load factor per vehicle type)		
	23.4 t	86.2 m^3
	34.6 t	135 m^3
	48.7 t	180 m^3
Fuel consumption		
	l/tonne-km	l/m^3-km
Semitrailer	0.0155	0.0038
Road train	0.0143	0.0032
HCT	0.0104	0.0025
Emissions		
	gCO_2/tonne-km	gCO_2/m^3-km
Semitrailer	40.89	10.11
Road train	37.86(−7.4 %*)	8.36 (−17.3 %*)
HCT	27.33 (−33.2 %*)	6.65 (−34.2 %*)

*Comparison against semitrailer.

No clear economy of scale in economic performance was identified in the sample. Based on the analysis, road trains appear slightly costlier to operate per tonne-km or m^3-km than semitrailers. HCTs were found to have lower costs per tonne-km than semitrailers, whereas semitrailers were found to be the most competitive in volume-based transports. This somewhat surprising result could be explained by the different nature of the businesses for the different vehicle categories.

Unlike in most of Europe, road trains have been allowed in Finnish national traffic for a long time. For this reason, the market has adjusted in a way that different vehicle types have mainly specialised in the type of transport activities they are most suitable and cost competitive of. A semitrailer tends to be mainly used in the simplest transport activities, whereas road trains are often used in more specialised transports such as chemical transports. This affects the level of key cost components such as capital costs (caused by more specialised vehicles) and salary costs (caused by additional competence requirements of the driver). In case these requirements would be applied to semitrailers, they would most likely reduce their cost advantage to some extent. Because of the higher total costs of larger vehicles, they also require a high load factor to be competitive. This is one of the factors limiting the economic potential of HCTs. As various types of vehicles are used, it could be assumed that to some extent there is a natural split of different vehicles – dependent on the division of different transported goods.

In fuel consumption per tonne-km or m^3-km, the economy of scale of larger vehicles is clear. Road trains were found to be more fuel efficient than semitrailers, and HCTs were the most fuel efficient. Fuel efficiency of HCTs was found to be 33.2 % better in mass-based transport and 34.2 % better in volume-based transports compared with semitrailers. Road trains were around 7.4 % more fuel efficient in mass-based transport and 17.3 % in volume-based transport than semitrailers. This is roughly on a same scale than the previous estimates of Lindt et al. (2017). Regarding fuel efficiency, it was also found that increasing the size of the vehicle increases fuel consumption less in volume-based transport than in mass-based transport. Even if this finding is based on basic physics that more power is needed to move increased mass, this still implies that the benefits of increasing the size of the vehicle would be higher in volume-based transport, obviously assuming sufficient fill rate.

From an environmental perspective, the results show that HCTs have the lowest fuel consumption per unit of transport performance. Thus, the key takeaway is that because CO_2 emissions are directly connected to fuel consumption, HCTs have the highest reduction potential of CO_2 emissions when transport performance is concerned.

The results contribute to transport policy dialogue both within and outside EU, as road transport is a significant source of greenhouse gases and the need to reduce the CO_2 emissions of road transport is urgent. Even though road transport could be decarbonised by electrifying HGVs or powering them with hydrogen or other alternative fuels in the long term, these technologies are still not widely used. Electric HGVs are expected to become cost competitive against diesel −driven vehicles in the medium term, but the transition is still in its early phases.

Therefore, expanding the size of vehicles provides a short-term solution for improving the energy efficiency of road transport. From an EU perspective, this is an exceptionally timely discussion because the Weights and Dimensions Directive (European Commission, 1996) is currently being renewed. From the perspective of energy and environmental efficiency, it might be beneficial to consider expanding the allowed maximum measures and masses or, at least to retain the current possibility for exceptions in national traffic. Even if road transport were to be electrified in the future, energy efficiency of larger vehicles is important because electricity production capacity has turned out to be a challenge.

The efficiency of HCTs and road transport in general has been linked to many other branches of transport policy. One of the most prominent arguments against increasing the size of heavy goods vehicles is their potential impact on modal choice (Meers et al., 2016; Sanchez Rodriques et al., 2015), hence increasing the modal share of road transport. However, as the results of our research have shown, the cost competitiveness of larger vehicles is not that obvious but instead depends on the context. For this reason, it could be argued that size alone is not sufficient to cause a modal shift. As an indicator of this, the modal share of rail transport in Finland is above the EU average, even though Finland is one of the countries where road trains and HCTs are allowed. Another argument against a major modal shift is the distance distribution of European road transports.

According to Eurostat, more than 75 % of road transport operations in Europe travel a distance of less than 150 km, and close to 90 % travel less than 300 km that is far from the usually considered (see for example Rodrique, 2020) distance threshold between road and rail transport. This implies that most of the road transport is locked to the road. At the same time, the small portion of longer road transport accounts for a major share of the emissions. Combined, it would be rational to consider different policies for these different submarkets. For long-distance transports, policies could guide towards a modal shift, whereas for shorter distances improved energy efficiency would imply the gains with HCTs as part of the solution. That could also limit the rebound effect (Llorca and Jamasb, 2017). This is demonstrated by the experiences in Finland, where the shift has taken place within the road transport volumes (Traficom, 2022) rather than between modes.

Introducing HCTs in Europe would be a challenge because much of the existing infrastructure is not designed for them. This includes the weight limits of bridges and dimensions of roundabouts and intersections. Even if HCTs would be allowed, they would be able to operate only on a limited part of the road network. This would limit their operational efficiency and potential, as well as restrict the shift to road transport away from other transport modes.

Finally, HCTs have also been opposed based on traffic safety reasons (Castillo-Manzano et al., 2021), with the argument that a larger vehicle is more destructive in the case of an accident. However, because road trains and HCTs seem to be able to operate with a relatively high fill rate, it would seem that, in practice, increasing the size of the vehicles would mean fewer vehicles on the roads. This would mean a lower probability for an accident including a heavy goods vehicle.

The current research has also its limitations. The survey sample was collected from a single country, albeit from one of the two EU countries that have allowed HCTs in national transport. This can also be seen as a strength because all the respondents face similar market conditions. At the same time, this geographic limitation must be taken into account when applying the results to other markets because they might behave differently. On the other hand, the Finnish market provides a real-life example of how the road transport market might look like in case longer and heavier road freight vehicles were allowed.

CRediT authorship contribution statement

Tomi Solakivi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lauri Ojala:** Writing – review & editing, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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