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A cost benefit model for high capacity transport in a comprehensive line-haul network

David Lindqvist, Marwan Salman and Rickard Bergqvist[*]

Abstract

The objective of the paper is to analyse the potential of introducing High Capacity Transport (HCT) within a comprehensive line-haul network. Barriers and enablers have been identified, and a cost benefit model has been developed. The model considers environmental performance, socio-economic costs and operational costs and has been applied to a Swedish context and case study. The findings reveal that HCT can contribute to the development of road transportation in the perspectives of energy consumption and emission releases. It can further strengthen the trade and competitiveness of Swedish hauliers, as the introduction can provide a more cost-efficient system for all actors, including the transporter. However, the potential is largest when longer vehicles are meticulously and scrupulously introduced on a designated network alone.

Keywords: Road haulage, High capacity vehicles, Transport energy consumption, Freight transportation performance, Longer vehicles, Cost benefit analysis

1 Introduction

Road freight transport is currently the dominant mode of transport in many countries, including Sweden. Continued growth in road freight transport is further expected in many regions, and a large part has derived from the trend of e-commerce. This development is equivalent to an increase in the total number of driven tonne-km and vehicle-km linked to the transportation of goods [1], which brings consequences that will impact society, the economy and the environment.

Nearly half of the released CO_2 emissions in Sweden are derived from the transportation sector, for which road transport covers almost 93% [2]. The Swedish government office has defined a climate target to reach the goal of zero emissions of greenhouse gases [3, 4]. Therefore, there is an urgent need for innovation regarding new approaches for conducting road freight. By increasing the maximum permitted weight and/or length of the trucks used to transport goods, there is potential to reduce negative aspects. The possibilities of High Capacity Transport (HCT) is an efficient practice to achieve a higher capacity in the road transportation network. The increased capacity will enable more weight and/or volume of goods to be loaded onto the trucks. The cost of transportation per unit of carried goods will be reduced along with the quantity of emissions and improved road safety, as fewer trucks are required [5]. This drive positive effects on transport costs and the environmental impact from the transport sector [6, 7].

HCVs release more emissions than conventional vehicles due to a higher consumption of fuel and energy needed; therefore, they also become more expensive per vehicle-km [8, 9]. Nevertheless, as loading capacity is greater in HCVs, fewer vehicles are needed to freight the same amount of goods that otherwise would have been transported by conventional vehicles. HCVs are, therefore, reducing total fuel and energy consumption, emissions and CO_2 per tonne-km [9–12]. The activities in a

* Correspondence: rickard.bergqvist@handels.gu.se
Industrial and Financial Management and Logistics, Department of Business
Administration School of Business, Economics and Law at University of
Gothenburg, P.O. Box 610, SE 405 30 Göteborg, Sweden

transport chain can evoke negative effects such as congestion, accidents, noise, infrastructure wear and tear, air pollution and other environmental impacts [13]. These effects are elements that form external costs. One way of reducing emissions is to explore the possibilities with HCT as a solution from a socio-economic and environmental perspective [6]. Strict requirements for permission to use HCVs, increased carefulness when driving larger and heavier vehicles, and driving on larger and safer roads while utilising greater safety equipment are also possible factors for a reduced risk and, thus, increased safety for the largest vehicles, resulting in decreased accident costs in total [7, 14–18]. It can also be seen that the largest vehicles in Alberta, Canada, have a 58% lower risk for accidents than standard semi-trailer combinations [19]. Similar findings have been presented in a more recent study analysing the safety of HCT traffic in Sweden and further claims that longer vehicles tend to be safer with less risk for accidents [18, 20–22], independent of any modal shift traffic safety increase due to fewer trucks in traffic [23]. Finland which has been permitting heavier HCVs since 2013 and longer HCVs since 2019, has only reported positive experiences concerning road safety. The interactions with tunnels, bridges and roads (e.g. road crossings, roundabouts, country roads with high accidental risks or highways with high intensity of traffic) must also be considered even if the physical infrastructure is affected little when implementing longer vehicles as longer vehicles contain more axles and the load can be more evenly distributed and the load per axle decreases [24, 25]. However, the impact on infrastructure depends on the national standards and may vary between countries. Nevertheless, However, the financial impact is the most important factor for the transporters. Knight et al. [6] compared the operating costs of different vehicle types, clearly showing that HCVs have the lowest operating cost per tonne-km. However, these calculations have been made on the assumption of 100% payload and utilisation. The fill rate and utilisation of long and heavy vehicles (LHVs) and HCVs are an important factor that is simultaneously a challenge for many hauliers. It is hard to realise an average fill rate above 70% [26], because flexibility must be ensured to handle fluctuations in demand [27]. As more goods are transported in one vehicle, the various costs related to the vehicle are levelled out over a larger quantity of carried goods. Previous studies have shown that the cost per tonne-km is reduced by 20–33% and fuel consumption by 25–35% when HCVs longer than 26 m are used [19].

In recent years, several HCT programmes have been carried out in Sweden by, among others, Closer, Swedish Transport Agency, Swedish Transport Administration, Transport Research Institute (VTI), Vinnova and Trivector.

These have focused on the positive and negative effects of introducing High Capacity Vehicles (HCVs) on Swedish roads. HCT pilot case studies have been conducted in, for example, the ETT project [28], Duo2 project [24], One Coil More [29] and the case of Jula [30].

There are diverse attitudes and points of view found among different stakeholders regarding HCT. Those who favour the use of HCVs claim it will contribute to an increased transport efficiency per tonne-km with reduced operational costs for hauliers as well as environmental impacts. Those who disagree claim that a potential increase in transport efficiency will be neglected because of a greater demand for transport, a modal shift to road transport and needed infrastructure investments from society [31]. Historically, the result from permitting larger vehicles in Sweden to 25 m has however been positive in terms of social benefits and other externalities, as it has resulted in fewer vehicle-km per given amount of tonne-km [32]. Furthermore, if pre- and post-haulage were to be performed by HCVs rather than the standard haulage setup, there would be potential to decrease the total costs for intermodal transport for the shippers by 10% when the haulage accounts for about 20% of the total costs of the transport chain. This change has the potential to create a substantial modal shift, as the break-even point is relocated, and intermodal rail-road transport becomes more competitive. If regulations for HCT were more generous regarding vehicle length, this could contribute to better cost efficiency for intermodal transport by addressing the problem of last mile efficiency [30, 33].

1.1 Objective

While the benefits and risks of HCT can easily be calculated upon singular and shorter routes, there is limited research on more complex and comprehensive networks. The gross potential of using HCT also varies if the maximum weight and/or length are changed. The reason for this is that goods might have different limitations and are only affected when the capacity increases in the relevant aspect [1, 34, 35]. HCVs can, therefore, only be defined by length, weight or both. As grouped and mixed goods often are limited by volume and loading metres (LDM), in this paper, HCVs are defined as *only* longer vehicles and not as heavier *and* longer vehicles.

The objective of this paper is to develop and present a model that calculates the costs and benefits of an introduction of HCT within a comprehensive line-haul network and identify the barriers and enablers. This has been applied to the line-haul network of DHL Freight Sweden (DHL) to "provide an understanding of how benefits can be achieved with respect for different aspects that is to be viewed from a system perspective." This is vital to create an understanding of how longer

trucks and their increased capacities affect the full system with respect to all stakeholders. The research question is defined as: What are the potential benefits and disadvantages of HCT from the perspective of operational costs, environmental performance and external costs?

2 Method

In recent years, DHL has experienced a rapid yet stable growth in grouped goods and packages as a result of the development of e-commerce, and the terminal in Malmö alone had an increased demand of 35% during 2018. DHL had an average fill rate utilisation of 65%, including journeys with fully empty trucks, during 2017 and 75% during 2018 and is recognising an urgent need for increased capacity [36]. The growth has been challenging due to capacity restrictions, and there is currently a high average fill rate in the haulier's fleets.

To address the research question and the objective of the report, primary data have been gathered through interviews and data retrieval from DHL's ERP system. The data contain all freight transports expressed in volumetric weight between all 25 terminals (Fig. 1) and 600 relationships during 2018 in Sweden. Secondary data were gathered through other reports and research publications. For comparison reasons, reports from Finland, the UK, Australia, the Netherlands and previous projects in Sweden have been examined. Finally, the Swedish Transport Administrations research study [37] regarding HCT in Sweden has been analysed and validated.

To provide an understanding of how HCT could influence the comprehensive line-haul network, calculations between each terminal's relationship have been studied and analysed. HCVs are defined as only longer vehicles in the calculations, as the carried goods are primarily limited by the volume. Three scenarios were then analysed. The first scenario represents the present situation in which all freight is carried by solely LHVs that are currently used and permitted, with the present costs as is. The second scenario represents freight carried with solely HCVs, which leaves the third scenario to compare the cost per transport if carried by LHVs and/or HCVs and appoint the most cost-efficient alternative. This scenario is, therefore, referred to as 'optimal' and is a mixture of both configurations revolving around the most suitable and cost-efficient alternatives.

The different scenarios are developed to illustrate transparency between the results. Only one result alone is not sufficient enough to compare the costs of LHVs with those of HCVs. There might, for example, exist a more optimal equilibrium between them. The fact that each terminal's traffic differs from day to day in relation to the demand for freight also indicates that the suggested setup of vehicles could be a combination of both

LHVs and HCVs and, thus, not just one of the two (Table 1).

2.1 HCT cost benefit model

The proposed model calculates the relative costs from a system perspective in which the operational costs for hauliers and the external costs for society are covered in the equations and functions of the model. The external costs are derived from the outcome of the operational premises' fuel consumption and distance between the origins and destinations and are thereafter used in combination with theoretical findings that describe the externalities in absolute numbers. To gain transparency, a sensitivity analysis approach is further applied and calculated upon as a foundation of the resulting analysis in the three scenarios.

The fundamental variables of the calculations and formulas used are hereafter explained in detail to fulfil required reliability to the developed model. Every calculation and formula are performed for each relationship and day for every terminal in the network.

The cost parameters were based primarily on Flodén [39], Asmoarp et al. [40], Adell et al. [41], Johansson and von Hofsten [42], and the Swedish Transport Administration [43]. The costs were adjusted to the financial inflation through the Sweden Statistics price calculator [44] to 2019 prices. The fixed costs were broken down per km, and the variable costs were broken down per km or hour. The calculations related to operational costs were derived from DHL and are hence justified and validated. The accident costs were derived from calculations by Flodén [39] and other external costs from Adell et al. [41].

The first step was to create two formulas to break down the volumetric weight to variables that are easier to apply in the calculations. It was most logical to convert the need of capacity in volumetric weight to LDMs due to the characteristics of DHL's carried goods. To calculate the needed capacity of trucks in terms of LDMs, there must be a factor representing the weight of the goods equivalent to one LDM. This variable was used as the base in all further calculations, as this illustrated a realistic perspective of how the transportation of freight is planned and handled in the context of DHL's line-haul operations. The average weight per LDM during 2018 was based on the value of 1300 kg.

$$Required\,LDMs = \frac{Volumeteric\,weight}{Kg\,per\,LDM}$$

When the volumetric weight was recalculated to LDMs, it became possible to calculate the number of vehicles needed, as the required capacity to saturate the demand for freight transport was given. The next step was to calculate the demanded vehicles needed for each relationship
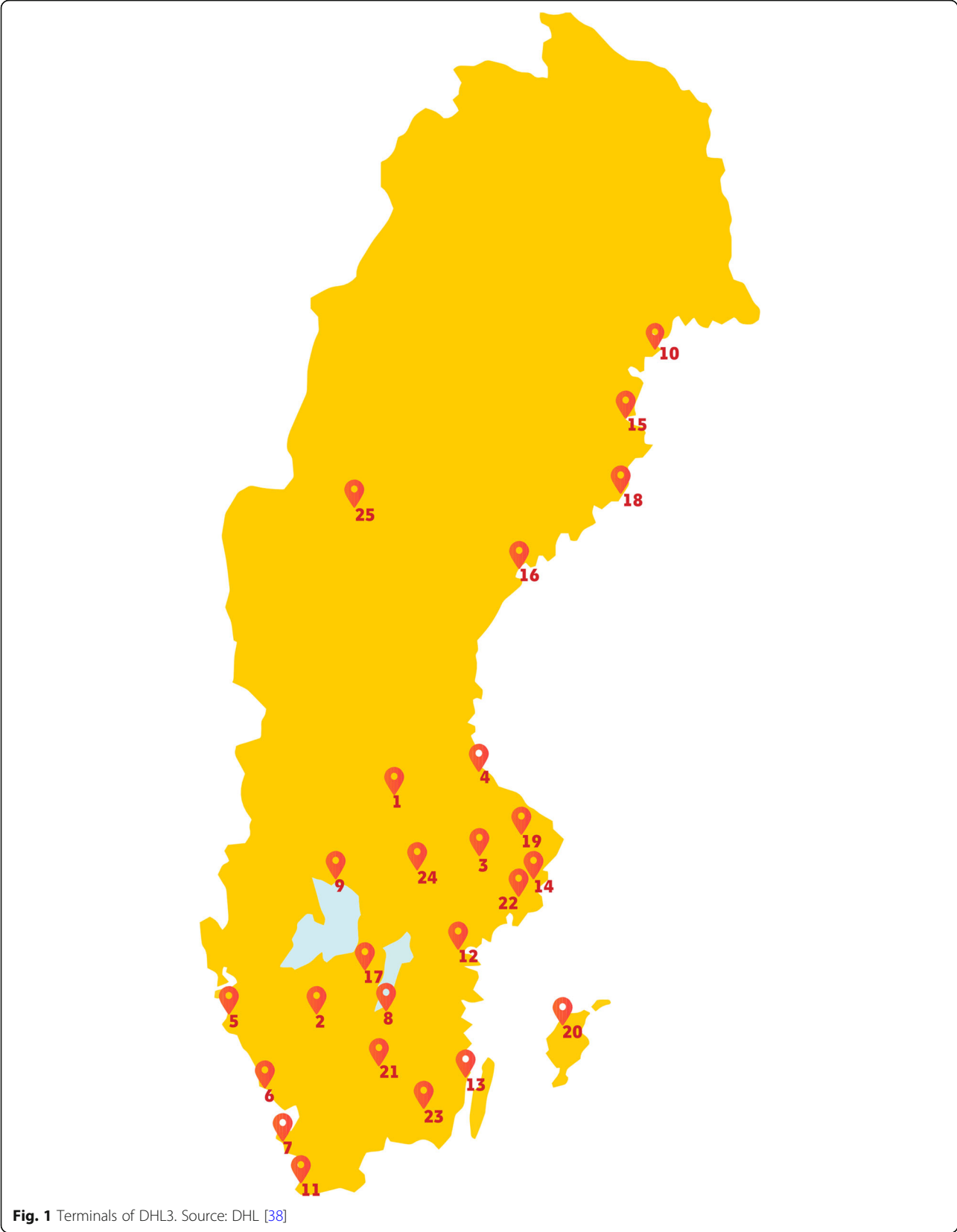
Fig. 1 Terminals of DHL3. Source: DHL [38]

Table 1 Map of the different Scenarios

	Scenario A *Solely LHV*	Scenario B *Solely HCV*	Scenario C *Optimal*
Vehicle Type	LHV 64 t / 25.25 m	HCV 64 t / 34.5 m	LHV 64 t / 25.25 m HCV 64 t / 34.5 m
Extent	Full Terminal Network	Full Terminal Network	HCV only operates when it is more cost efficient than LHVs
Description	A current situation analysis and net present value in which only LHVs are permitted to operate in the terminal network	A situation analysis in which HCVs are introduced in the full terminal network and replace all LHVs	A situation analysis in which the vehicle most optimised for every single trip between two different terminals is used, with respect to capacity and operational costs

and day in the terminal network. This was calculated for both LHVs and HCVs in order to ultimately have the possibility to compare the effects of choosing either of the two. Also, the average fill rate was included in this formula to achieve a truthful output.

$$LHV_N = \frac{Daily\ demand\ LDMs}{LHV\ trailer\ length * Average\ fill\ rate}$$

$$HCV_N = \frac{Daily\ demand\ LDMs}{LHV\ trailer\ length * Average\ fill\ rate}$$

This resulted in non-absolute numbers, as the demand, for example, could be 4.39 for LHV and 3.15 for HCV. These numbers had to be rounded off to the upper absolute integer value, which, in this example, would result in 5 LHVs and 4 HCVs. Therefore, a formula applied to systematically round up the numbers was added to the model.

$$Required\ vehicles\ in\ absolute\ numbers = Roundup\ (Demanded\ vehicles; 0)$$

The upcoming step was to calculate the costs of the capacity for both vehicle types. The cost structure variables used in the model were divided into fixed costs, distance-based variable costs and time-based variable costs (see Table 2).

The result from interviews with DHL implied that the vast majority of trucks are used throughout their full lifetime which is between six to 9 years. The yearly depreciation has been calculated through a degressive depreciation method and was used as the depreciation amount equal to ((degressive 25% x amount of depreciation days x base of depreciation) divided by (100 ×

360)) over 7,5 years which also resulted in a residual value of 12%. The base of depreciation is equal to price of procurement subtracted with each continuous period's added value of depreciation. The costs, with aggregated fixed and variable costs (FC and VC), for each vehicle type was then calculated as:

$$FC_h = \frac{(Yearly\ depreciation + Cost\ of\ capital)}{Utalised\ hours\ per\ year}$$
$$VC_{km} = Tires + Repairs + Depreciation + \left(Fuel_{l/km} * Fuel_{SEK/l}\right)$$
$$TVC_h = Salary + Other + \left(VC_{km} * Average\ speed_{km/h}\right)$$

The total cost of transportation, if operated by LHVs or HCVs, could then be calculated by including the number of vehicles needed in absolute numbers with above equations to obtain the total cost per relationship and day:

$$TC = FC_h + \left(\frac{Distance}{Average\ speed_{km/h}}\right) * TVC_h$$

The last step in the calculation of the operational cost premises was to apply a logical test through an IF-function. This function checked whether a condition was met and returned a value reliant on the falseness or trueness of that condition. This function was primarily used to acquire the data of the optimal vehicle type for the optimal scenario. The cost-value of HCV was returned when the value of the total operational costs for HCV was less than LHV, and the value of LHV was returned if this was false.

Table 2 Variables comprehended in the suggested Cost Benefit Model

	Variables		
	Fixed costs	Distance-based variable costs	Time-based variable costs
Criterias	Price of procurement	Tires (SEK/km)	Salary and payroll tax (SEK/hour)
	Life span	Repair and maintenance (SEK/km)	Other, i.e. taxes, insurance, equipment etc. (SEK/hour)
	Yearly depreciation	Fuel consumption (L/km)	
	Average tied up capital	Fuel costs (SEK/L)	
	Cost of capital	Depreciation (SEK/km)	

$$\text{IF } (logical\_test; value\_if\_true; value\_if\_false)$$
$$\text{IF } (TC_{HCT} < TC_{LHV}; value\_if\_true\_TC_{HCT}; value\_if\_false\_TC_{LHV})$$

The variables of emissions were presented in kg/litre fuel and cost/kg emissions and recalculated to cost/vehicle-km to be applied to each transport by simply being multiplied to the needed number of vehicles and distance.

The first step calculated each emission's total weight for both LHV and HCV. By including variables such as distance between the origin and destination, fuel consumption per km for each vehicle type, the emission release for a certain oxide per litre and the number of vehicles needed for that particular transport, the released amount of emissions in kg was obtained.

$$Emission_{X_{kg}} = \left(\left(Distance \times Fuel\ consumption_{LHV/HCV} \right) \times Emission_X kg/l \right) \times Demand_{LHV/HCV}$$

The next step calculated the cost for that particular emission and transport. These steps were calculated on each row of data between every relationship and for each particular transport. The result could then be aggregated and presented in different ways, for example, for a certain relationship, a certain weekday, for the whole network or for a designated network alone.

$$Emissions_{SEK} = Emission_{X_{kg}} \times Emission_X SEK/kg$$

Road wear could easily be added in the externalities by just multiplying the cost per km per LHV or HCV with the total vehicle-km. The road wear of an HCT can increase if the maximum weight limit is increased but not the length limit, or even decrease if the maximum length limit is increased but not the weight limit.

$$Road\ wear_{SEK} = \left(Road\ wear\ SEK/km_{LHV_{HCV}} \times Distance \right) \times Demand_{LHV/HCV}$$

Cost of accidents was re-calculated upon the amount of accidents in 2017 with a deduction of the risk valuation cost of, as the reviewed literature suggests, an approximately 50% reduced risk of accidents in larger vehicles. The Material Cost, Risk Valuation and Cost of Accident for fatal, severe and slight accidents were summed and divided by the total vehicle-km driven in 2017 of trucks with a minimum gross weight of 3.5 t. This data was obtained from Transport Analysis, a Swedish government agency responsible for official statistics in transports. The equation provided an accident cost per vehicle-km.

Calculated accident cost per vehicle-km and vehicle type was then converted to a total cost for the transport, if operated by HCV or LHV.

$$Accident\ cost_{SEK} = \left(Accident\ cost\ SEK/km_{LHV/HCV} \times Distance \right) \times Demand_{LHV/HCV}$$

At last, the total external cost for each vehicle type was calculated by summing up the total cost of emissions, road wear and accidents.

$$Total\ external\ cost_{LHV/HCV} = TC\ Emissions_{LHV/HCV} + TC\ Roadwear_{LHV/HCV} + TC\ Accidents_{LHV/HCV}$$

All variables applied in the model can be found in Additional file 2.

3 Results

Following the principles of the suggested cost benefit model, calculations reveal that HCT is not always more suitable and could, in fact, become costly. The resemblance between different fill rates in LHVs and HCVs has been compared. A 100% fill rate LHV based on loading metres corresponds to a 76% fill rate in an HCV. It can, therefore, be determined that an HCV must be filled with more than 75% to become economically feasible. This has been validated and developed in Table 3.

However, the general approach in the model is based on the current average fill rate of 75% in LHVs. According to DHL and previous literature, it is not reasonable to have an average fill rate of 100% (c.f [26].), as there must be a certain volume available to manage fluctuations and gain some flexibility. The principles and motivations behind the applied fill rates in this particular case are based on the available LDMs in DHL's current operations. The fill rate of 75% in LDMs is, in an LHV, equal to 15.6 LDM ($20.8 \times 0.75 = 15.6$), thus there are 5.2 LDMs still available ($20.8 - 15.6 = 5.2$). It is, therefore, assumed that 5.2 LDMs are needed in an HCV to ensure the same flexibility and to secure extra capacity for fluctuations in demand and variations. In examining the fill rate an HCV would have, if available space must be equal to 5.2 LDMs, an average fill rate of approx. 80% (($27.3 - 5.2$) / $27.3 = 0.809$). Therefore, a fill rate of 80% was used for the HCT's calculations. Based on this foundation, the model presents a potential cost reduction of 6% if HCT is introduced. However, the costs increase if HCVs replace LHVs on the full terminal network (see Table 3). The evidence further clarifies the importance of carefully introducing HCT, as it must only be

$$Accident\ cost_{SEK/km} = \frac{\left((MC_{F\alpha} + RV_{F\alpha} + CoA_{F\alpha}) \times O_{F\alpha} + ((MC_{Sev} + RV_{Sev} + CoA_{Sev}) \times O_{Sev}) + (MC_{Sli} + RV_{Sli} + CoA_{Sli}) \times O_{Sli} \right)}{Total\ Vehicle\ km}$$

Table 3 Feasible fill rates for converting to HCT

Average Fill Rate		Scenario A	Scenario B	Scenario C	Savings
LHV	HCV	(Soley LHV)	(Soley HCV)	(Optimum)	(Sc A - Sc C)
100%	75%	100%	110%	100%	0%
100%	85%	100%	108%	98%	2%
100%	95%	100%	106%	97%	3%
100%	100%	100%	105%	97%	3%
75%	80%	100%	102%	94%	6%

implemented in the appropriate locations and only where it is actually required.

The results of the environmental performance disclose a potential in the environmental performance as well. However, the results here are very interesting, as the potential for solely HCVs to be used in the full terminal network was demonstrated (see Table 4).

If the environmental performance is converted to the financial impact that falls on society, it can be seen that the external costs per type of oxide are reduced. Accidental costs are mostly affected by solely using HCT, as HCVs have much lower risks of being in an accident compared to LHVs (see Table 5).

To conclude, there is potential for HCT, which confirms previous research related to HCT. There are, however, still some negative impacts with HCT, as is illustrated when solely HCVs are used in the terminal network. If HCT is only used when suitable in the transport relationships, the number of transportations can be reduced by almost 10% of vehicle trips per year. Table 6 illustrates the different outcomes produced by the model. The darkest cells illustrate negative impacts, while lighter cells illustrate positive impacts and reductions in relation to current scenario of solely LHVs in operations. HCT does not result in a positive effect in all 600 relations between the 25 terminals in the system, as showed in Table 6. As the presented data demonstrate that a sole operation of HCVs everywhere is not economically justifiable due to carried volumes, it is logical to assume the potential should be larger in terminals with high volumes. If this is tested by reducing the data in the model of all 25 terminals to only a designated

network of the six terminals with the highest volumes, a considerably greater potential is identified. Even when HCVs are solely used in the designated line-haul network of the six largest terminals, the costs will still be reduced due to the large volumes, which supports the assumption of high volumes being a prerequisite to achieve the benefits of HCT.

3.1 Analysis

The calculations are only based on the costs of LHVs in comparison to HCVs, and this could be a weakness of the model. For example, even if a smaller vehicle like a van or small truck would be sufficient in practice, the model would still calculate the cost for either an LHV or HCV. Also, if the model calculates a need for 3.15 HCVs in a certain relationship, the output would use 4 HCVs and not 3 HCVs and 1 LHV as would be done in reality. Therefore, in these occasions, the operational costs and environmental effects would be less than the result given by the model, which is considered as a weakness. The costs of handling and coupling operations at the terminals are also excluded in the model, but this should be considered as an important factor when implementing HCT. These activities could be handled by a tugmaster operated by a terminal employee or the truck driver. The coupling will take more time for an HCV than for an LHV; as there are 2 trailers instead of 1, this will affect the lead times, which could affect the system. The handling cost for HCVs is most likely higher than LHVs. However, as the vehicles are only longer, standardised equipment and chassis across the industry can still be used which reduces the handling time and cost. The

Table 4 Environmental Performance

	Scenario A	Scenario B	Scenario C	Differential	Differential
	(Soley LHV)	(Soley HCT)	(Optimal Setup)	(Sc.A - Sc.B)	(Sc.A - Sc.C)
Fuel (L)	100%	97%	93%	3%	7%
CO_2 (kg)	100%	97%	93%	3%	7%
Nox (kg)	100%	97%	93%	3%	7%
HC (kg)	100%	96%	93%	4%	7%
PM (kg)	100%	97%	93%	3%	7%
SO_2 (kg)	100%	96%	93%	4%	7%

Table 5 External Costs

	Scenario A (Solely LHV)	Scenario B (Solely HCT)	Scenario C (Optimum)	Differential (Sc A - Sc B)	Differential (Sc A - Sc C)
CO_2	100%	97%	93%	3%	7%
NOx	100%	97%	93%	3%	7%
HC	100%	98%	93%	2%	7%
PM	100%	96%	93%	4%	7%
SO_2	100%	96%	93%	4%	8%
Total Cost (Emissions)	100%	97%	93%	3%	7%
Road Wear Cost	100%	90%	93%	10%	7%
Accident Cost	100%	69%	90%	31%	10%
Total External Costs	100%	85%	92%	15%	8%

management structure, logistics setup and other equipment (e.g. tugmaster) does also affect the time and cost for coupling and handling. Nevertheless, as the number of vehicles is reduced with the increased capacity in HVCs reduces the number of trips required per day given the demand, hence also the number of vehicles that must be handled. The weighed cost can therefore be balanced out or even become an advantage for HCT.

Table 7 and Fig. 2 account for the sensitivity analyses conducted. Table 7 presents how the total costs in the optimal scenario change when different variables are decreased or increased by 10% and 30%. For example, if the costs regarding fuel increased by 30%, the findings would result in an increase of 9% in the total costs in the optimal scenario. The variables of fuel, salary, utilised hours and average speed have a significant effect in all scenarios on the total cost. The results demonstrate which variables affect the model the most and what parameters are highly sensitive to changes. The environmental effects would not be affected by price adjustments in different parameters and are, thus, not accounted for in the calculations.

Another aspect that would have some influence on the total cost is the fill rates of the vehicles. The fill rate in

the vehicles determines how much of the available LDMs are used for each transport. In the model, the fill rates are based on the total LDMs available, which is equivalent to 20.8 m in an LHV and 27.3 m in an HCV. To analyse how the fill rate affects the total cost, a sensitivity analysis was performed exclusively for the fill rates (see Fig. 2). Figure 2 illustrates how different fill rates over the various scenarios affect the total cost when adjusted over the span of +/− 25% from the destined fill rates of 75% in an LHV and 80% in an HCV. When these fill rates are used, both vehicles have an excess capacity of approximately 5.2 LDMs. The findings show that there is more to lose if the fill rate decreases than there is to gain in an increase. If only LHVs are used in the terminal network, a decrease of 25% of the fill rate would result in a total cost increase of 10%. If the fill rate increased by 25%, the total costs would decrease by 5%. This relation is comparable with the two other scenarios, but the effect here is slightly less extensive. If the fill rates in the optimal scenario increased by 25%, the total cost would decrease by 3%, and if it decreased by 25%, the total cost would increase by 7%.

Based on LDMs, an HCV of 34.5 m increases the capacity by 31%. Kyster-Hansen and Sjögren [19] roughly

Table 6 Summarised result of an introduction of HCT in a full vs designated network

	Scenario A Soley LHV	Full Terminal Network		Designated Terminal Network	
		Scenario B Soley HCT	Scenario C Optimum	Scenario B Soley HCT	Scenario C Optimum
Total Operational Costs	100%	102%	94%	86%	82%
Fixed Costs	100%	105%	94%	89%	84%
Distance Based Costs	100%	107%	94%	90%	84%
Time Based Costs	100%	92%	93%	77%	78%
Overall Environmental Cost	100%	85%	92%	71%	75%
Emissions	100%	97%	93%	81%	80%
Congestion	100%	123%	95%	107%	94%
External Costs Related to Emissions	100%	97%	93%	80%	79%
External Costs Related to Infrastructure	100%	90%	93%	76%	77%
External Costs Related to Safety	100%	69%	90%	58%	68%

Table 7 Sensitivity Analysis

Scenario C (Optimum)		Change in total costs, when each variable is adjusted by 10 or 30 percent				
		-30%	**-10%**	**0%**	**10%**	**30%**
	Tires Ratio	99%	100%	100%	100%	101%
	Repair Ratio	98%	99%	100%	101%	102%
	Fuel Ratio	91%	97%	100%	103%	109%
Adjusted Variable	**Depreciation Ratio**	99%	100%	100%	101%	102%
	Salary Ratio	92%	97%	100%	103%	108%
	Others Ratio	99%	100%	100%	100%	101%
	Average Speed Ratio	122%	106%	100%	95%	88%
	Utalised Hours Ratio	109%	102%	100%	98%	95%

estimated a capacity increase of 50% to reduce transport costs by 15–20%. This is not supported by the results from this paper or research on line-haul networks that used volume as a constraint, as the calculated costs would only be 6% with an increase in capacity of 31%. However, the costs are reduced by 18% if HCT is only introduced in the relationships between the largest/most beneficial terminals. This also shows that the benefits of HCT are much larger when implemented only where it is truly required, which, in this particular case, would be in the six largest terminals.

The results produced are in line with those from the Swedish Transport Administration [37], which argued for opening up a larger network in southern Sweden for HCT. Results also confirm the prerequisites of large and frequent volumes for feasible HCT. This is illustrated in Fig. 3 where the six largest terminals of DHL are highlighted through darker markings.

Furthermore, better possibilities can be created to achieve economies of scale in the transportation network by consolidating more than one terminal in one freight transport, e.g. by connecting many of the terminals in southern and middle parts of Sweden (see the lighter markings in Fig. 3). To exemplify, if a transport is going from Malmö to Gothenburg, the vehicle will pass Halmstad before continuing towards Gothenburg. For instance, an assumption could be made that there is a demand to transport a trailer from Malmö to Gothenburg as well as a trailer from Halmstad to Gothenburg. A vehicle starting from Malmö with a length of maximum 25.25 m could then stop by Halmstad and add a second trailer to the equipage. In other words, if there are possibilities to collect an extra trailer, the LHV transforms to an HCV. This would improve the flexibility and decrease the lead time by improving allocation of capacity via dividing and coupling trailers. If there are no such possibilities due to demand in Halmstad, the vehicle just runs as a LHV. This idea can, if setup correctly and carefully, leverage the potential cost savings and also the efficiency of the terminal network from an environmental perspective. This can considerably reduce the costs and increase the quality of the service level. The extra interlink trailers located at
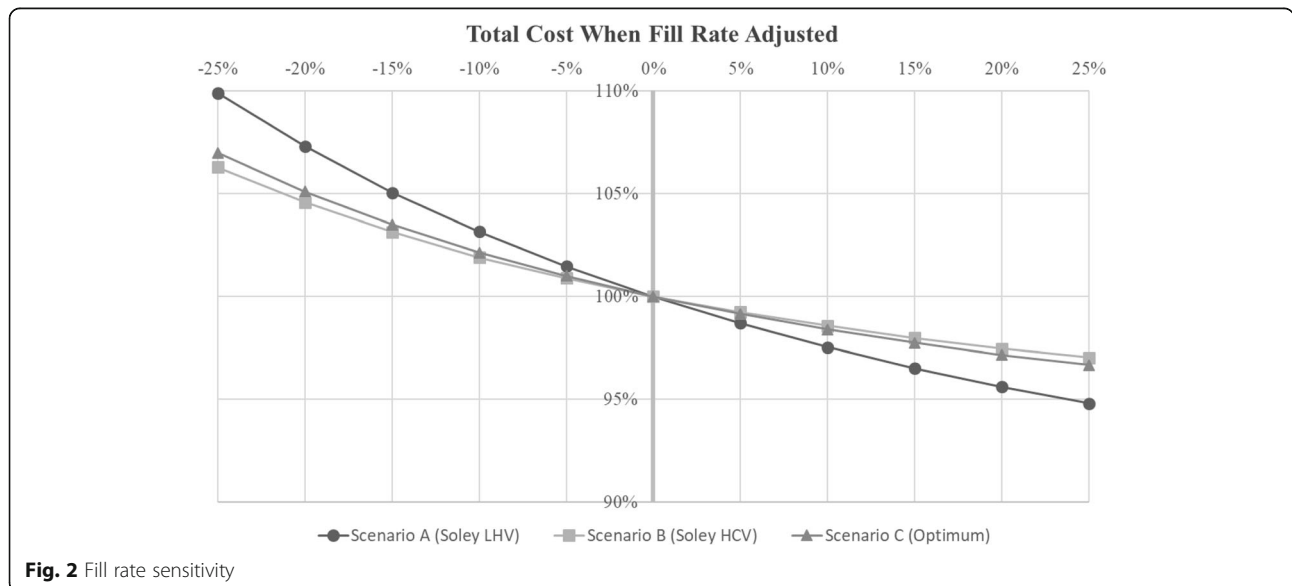

Fig. 2 Fill rate sensitivity

Fig. 3 Illustration of suggested designated roads to permit longer vehicles of 34.5 m [37]

some terminals also have the possibility to be reallocated to handle fluctuations. If the vehicle utilisation of HCVs can be further enlarged from an average of 80% in fill rate, the number of trips can be reduced even more. By driving past other terminals and consolidating goods, it is not impossible to achieve a fill rate above 80%. However, if Halmstad has a large volume of goods that are to be delivered to Gothenburg, it might still need an extra vehicle; carefulness is, therefore, vital in the planning. This strategy of implementation requires not only carefully performed capacity planning between each of the terminals of interest but also efficient flows of information between the terminals, hauliers and management. A deeper investigation would be required to understand, illustrate and discuss this complexity and its benefits. This appearance and structure are, however, identified and believed to add an extra level of flexibility in the terminal operating network.

HCT is an attractive solution from an environmental perspective, as it is believed to have the potential to minimise total fuel consumption, emissions and traffic congestion [45]. The findings of this report show that this is true, with all types of oxides reduced in the optimal scenario and even in the scenario that solely used HCVs. This is due to the reduced number of vehicles and, as the vehicles are only longer and not heavier, the rise of fuel consumption is only slightly increased (mainly because of different aerodynamics). This also results in a lower load per axle which, consequently, has a reduced tear on the roads and a reduced risk of accidents of HCVs. However, it can be argued that the results showing potential when HCT is solely used are not realistic nor feasible in reality, as there is no financial benefit in this for companies.

4 Conclusion

A cost benefit model has been developed to answer the research question and identify the benefits and disadvantages of HCT within a comprehensive line-haul network. The calculations and obtained result have been validated through final expert interviews with DHL Freight among others. The results show great potential with HCT. Furthermore, the model suggests that HCT can be implemented differentiated on designated segments/relations in the line-haul network. The study reveals and presents results that are relevant for the stakeholders and can hence be distinguished as a model applicable in a system analysis.

Based on the calculations made upon DHL's line-haul operations, the model is shown to be sensitive to the parameters of fuel, salary, speed and fill rate. The fill rate moreover reveals that it is vital to keep a high average fill rate, as the effects of the changes on the costs are not linear. This was illustrated when the fill rates were adjusted +/− 25% of both vehicle types. If the fill rate reduced from 75% to 56.25% in the LHVs, and from 80% to 60% in the HCVs, the costs would increase by 7%. However, if the fill rate increased from 75% to 93.75% in the LHVs, and from 80% to 100% in the HCVs, the costs would reduce by 3%. It also indicates that an external factor such as an economic recession could have a large effect on the usage of HCVs. Nevertheless, HCT has the possibility to reduce operational costs, improve environmental performance and, consequently, reduce the external costs. However, a prerequisite is that large volumes exist and remain frequent with little to no variation. This is further illustrated in Table 6, which presents a capability of reducing external costs by 8% if HCT is introduced in the full network. If many relations that do not have large volumes to transport are excluded, the external costs can be reduced by 15%.

In relation to limitations, the model does not take into consideration any costs of handling, coupling and such in terminals nor an optimal driving route for consolidations between different terminals. The model does not have any route planner algorithm and is dependable on

good quality of input data. The main argument for not including these types of costs is that it brings a level of detail to the model that is very hard to validate since there is no real work experiments and cases to study in order to get the proper quality of input data. Nevertheless, it is possible to further develop the analysis by including costs for the congestion and used space, terminal handling costs based on coupling and decoupling and by including the external costs for noise emissions, as more demonstrations are available. Future research could also focus on intermodality and its possible connection to HCT.

5 Supplementary Information

> **Additional file 1.** Literature Review.
>
> **Additional file 2.** External Costs (SEK).

Authors' contributions
DL and MS have made equally substantial contributions to the conception of the work. RB has contributed with experience and guidance throughout the paper, HCT tests and other vital information for the analysis of previous research. The author(s) read and approved the final manuscript.

Availability of data and materials
The datasets generated and analysed during the current study are not publicly available due to confidentiality but are available from the corresponding author on reasonable request and with permission from DHL.

Competing interests
The authors declare that they have no competing interests.

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