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The potential of high-speed rail freight in Europe: how is a modal shift from road to rail possible for low-density high value cargo?

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Abstract

Purpose: A fully electrified transport chain offers considerable potential for CO_2 savings. In this paper, we examine the conditions necessary to introduce a fully electrified, large-scale, high-speed rail freight transport system in Europe in addition to high-speed passenger trains, aiming to shift goods transport from road to rail. We compare a novel high-speed rail freight concept with road-based lorry transport for low-density high value goods to estimate the potential for a modal shift from road to rail in 2030.

Methods: To characterize the impacts of different framework conditions, a simulation tool was designed as a discrete choice model, based on random utility theory, with integrated performance calculation assessing the full multimodal transport chain regarding costs, emissions and time. It was applied to a European reference scenario based on forecast data for freight traffic in 2030.

Results: We show that high-speed rail freight is about 70% more expensive than the conventional lorry but emits 80% less CO_2 emissions for the baseline parameter setting. The expected mode share largely depends on the cargo's value of time, while the implementation of a CO_2-tax of 100 EUR/tCO_2eq has an insignificant impact. The costs of handling goods and the infrastructure charges are highly influential variables.

Conclusion: High-speed rail track access charges are a suitable political instrument to create a level playing field between the transport modes and internalize external costs of freight transport. With the given access charge structure, a reduction of the maximum operating speed to 160 km/h has a positive impact on the expected mode share of rail transport while it still reacts positively to a wide range of the cargo's time sensitivity (compared to a maximum operating speed of 350 km/h). The flexibility of rail freight's operating speed is important for an effective implementation. Further research should concentrate on time- and cost-efficient transhipment terminals as they have a significant impact on transport performance.

Keywords: High-speed rail freight, Multimodal freight, Modal split, Modal shift, Low-density high value goods

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1 Introduction

Without a significant shift to more efficient electrified transport modes and decarbonized energy generation, limiting the global temperature increase above 1.5 °C compared to preindustrial times is unlikely. In Europe, the transport sector accounted for 30.8% of the final energy consumption and 27.9% of greenhouse gas (GHG) emissions in 2017 with mainly fossil fuel powered road transport being the largest consumer and emitter (93.7% and 71.7%, respectively) [1]. Especially due to the increasing freight transport demand, same day delivery and reduction of warehousing, traffic is expected to grow in the future. However, the energy system must be radically decarbonised throughout all sectors within a very short time frame to achieve the climate protection targets [2]. In Europe today, rail freight transport emits 3.5 times less GHG emissions than its road counterpart and strikes with high energy efficiency [3]. It must extend its market share and enter cargo segments that belong to the realm of road transport to facilitate the required modal shift. Intermodal rail-road transport has been proposed as a solution in the past [4–8]. Going beyond, this paper examines the potential of a disruptive multimodal concept for the transportation of low-density high value (LDHV) goods via rail to gain new market shares.

1.1 Challenges and future markets

The market share of rail freight in the European Union decreased from 12.5% in 2000 to 11.3% in 2017 despite an increase in total freight transport performance [1]. This decline is related to the freight structure effect, which involves a transformation of the production structure from mass goods to high value cargoes [9]. Mass goods are still the classic market segment of conventional rail freight transport while it has been widely expected that LDHV cargo will continue to be solely subject to road transport [10–12]. Intermodal rail-road transport in Europe copes with average speeds of 18-30 km/h [3], high expenses for single wagonload transport and simultaneous reduction of railway sidings. Hence, in average, intermodal transport is competitive to unimodal road haulage only on distances larger than roughly 600 km [8]. However, the EU white paper "Transport" from 2011 aims at a modal shift from road to rail and waterways of 30% by 2030 and 50% by 2050 for distances larger than 300 km [13]. These goals demand novel solutions for market segments that are not adequately addressed by conventional rail transport [14]. Schumann et al. [15] find the demand for LDHV goods transport to be 1.45 million tonnes per year on a representative trans-European transport corridor. In value terms, this accounts for significant 16.5% of the total freight transport market, currently solely transported by trucks.

1.2 Approaches to support rail freight's competitiveness

Jackson et al. [16], Islam et al. [17], and Islam and Zunder [18] point out that innovative transhipment technologies and logistics concepts, intermodal load transfer and general flexibility are crucial factors in supporting rail freight transport. Different developments such as higher speeds, automatic coupling systems, information and communication technologies or fast intermodal road-rail transhipment terminals can favour such a development [14, 19]. However, their implementation is lacking behind and there are only few examples of novel approaches to support rail freight transport. A higher operating speed is deemed especially important.

In 2017, Russian Railways has ordered baggage and mail wagons designed for maximum operating speeds of 160 km/h, which can significantly increase the average speed on long distances. In the past, the EURO CAREX project promoted a (very) high-speed rail freight (HSRF) concept with maximum speeds over 200 km/h for the transportation of air freight pallets in the retired TGV Postal trains, that is, however, currently not in operation.

In Italy, Mercitalia started "Mercitalia Fast" in autumn 2018: A high-speed freight point-to-point service with the HSRF-train ETR 500, transporting rolling containers (cf. used for postal service) between Maddaloni-Marcianise and Bologna Interporto. The trains run overnight at 180 km/h on the Italian high-speed network for time-sensitive deliveries, Monday to Friday in 3 h and 30 min. It is planned to extend the service in the future. In Austria and Sweden, other HSRF-projects are planned for express delivery of time-sensitive goods [20, 21].

Watson et al. [22] examine the future possibility of transferring freight from airlines to HSRF by analysing the operational and technical constraints associated with freight transport. They point out that HSRF could generate a new demand, a general increase in the utilisation of the transport infrastructure, an increase in revenue and a reduction in subsidies. However, the capacity of existing network to transport goods with HSRF and the technical and operational constraints of mixed transport need to be examined. They also conclude that the implementation and operation of HSRF is a costly business and it is doubtful whether infrastructure or railway undertakings alone will be able to set up such a freight service.

Cavagnaro et al. [23] further describe an innovative intermodal HSRF concept, compatible with high-speed passenger traffic, named "Hyperfreight". The concept involves a high-speed train and an automatized terminal-system for standard containers, which are fed into the rail vehicle from below with an elevation system.

The German Aerospace Centre also takes a holistic research approach in order to counter the current declining mode share in rail freight transport and overcome the above-mentioned key problems. The Next Generation Train

(NGT) CARGO is a driverless HSRF train concept with light-weight single wagons that load and unload palletised goods on roller floors for a fully automated, electrified logistics process [24]. The powerful, innovative transhipment infrastructure is able to perform cargo handling for a whole NGT CARGO block train within a few minutes and facilitates an efficient multimodal transport chain [25]. On unelectrified feeder tracks, the motorised single wagons can serve external logistics sidings and integrate themselves into a block train formation autonomously [26].

In the following, the NGT CARGO concept is used in the European HSRF reference scenario 2030. Section 2 introduces the applied methodology and Section 3 the examined scenario. The results for transport carrier performance and modal split under different assumptions are presented in Section 4, followed by a discussion and conclusion.

2 Methods

Previous research identified various attributes influencing the decision maker's mode choice in freight transport [5, 27–29], the most important being internal cost and haulage time. To assess these variables and the climate impact of multimodal and international freight transport chains, a multi-dimensional simulation model was developed. It is established as a detailed short-term performance calculation tool combined with an aggregate modal split model. The former uses detailed input data to determine performance attributes and their structure. The latter is implemented as a discrete choice model (Logit) based on random utility theory. Here, the shippers act as decision makers and intend to maximize their utility of freight transport on a scenario-specific origin-destination (O-D) pair. The utility is derived from micro-economic theory and is dependent on three performance attributes: internal cost, GHG emissions and transport time. External costs beyond emissions with global impact (e.g. network congestion, noise and local air pollution) are excluded because currently, these are not subject to the trade-offs in mode choice made by shippers. An inclusion thereof would alter the choice of transport mode to be the optimal solution for society as a whole which would most probably promote the rail mode. See Fig. 1 for a simplified illustration of the two-stage model structure.

2.1 Transport chain modelling

In every scenario, the performance of several transport chains comprising one or more transport modes on a defined O-D pair is calculated based on the characteristics of the attributed transport vehicles. There are four major mode types; road, rail, water and air (focus here: road and rail). Every transport chain is designed as a linear concatenation of L links which can hold one transport carrier tc of the corresponding mode each. Usually, the key aspect of research is attributed to the main carriage link(s). Beside the modes, a pseudo mode transhipment is integrated, which is not dependent on vehicles but on loading and unloading processes. Based on this set-up, the calculation of transport chain- and carrier-dependent performance attributes (i.e. C costs, EM emissions and T transport time) is carried out for each transport chain. These attributes consist of several impact factors as follows:

$$
\begin{aligned}
C = \sum\nolimits_{(l=1)}^{L} q_{tc_l} * [& ED(v_l, units_l * \rho, ed_{\max,0_{tc}}, \mu_{tc}, \lambda_{tc}, v_{max_{tc}}) \\
& * d_l * FP(fuel_{tc}, country_l) + c_{maint_{tc}} * d_l + c_{pers_{tc}} \\
& * TD(v_l, v_{maxtc}, d_l, stst_{tc}) + c_{cap_{tc}} * d_l + INFC(country_l) \\
& * d_l] + c_{trans-fix_l} + c_{trans-var_l} * (loading_l + unloading_l)
\end{aligned}
$$

$$(1)$$

$$
\begin{aligned}
EM = \sum\nolimits_{(l=1)}^{L} q_{tc_l} * [& ED(v_l, units_l * \rho, ed_{\max,0_{tc}}, \mu_{tc}, \lambda_{tc}, v_{max_{tc}}) \\
& * d_l * FEM(fuel_{tc}, country_l)] + em_{trans_l} \\
& * (loading_l + unloading_l)
\end{aligned}
$$

$$(2)$$

$$
\begin{aligned}
T = \sum\nolimits_{(l=1)}^{L} & TD(v_l, v_{maxtc}, d_l, stst_{tc}) + t_{trans-fix_l} \\
& + t_{trans-var_l} * (loading_l + unloading_l)
\end{aligned}
$$

$$(3)$$

Transport costs (1) comprise energy, maintenance $c_{maint_{tc}}$, capital $c_{cap_{tc}}$, infrastructure (e.g. track charges or road fees), personnel $c_{pers_{tc}}$, and transhipment costs. The first four components are dependent on the driving distance of that link d_l, while total transhipment costs depend on the number of units loaded and unloaded ($c_{trans-var_l} * (loading_l + unloading_l)$) plus a fixed fee to enter a transhipment point $c_{trans-fix_l}$. These costs occur in case that link l is of type transhipment. Personnel costs depend on the time demand calculated from the maximum velocity of the transport carrier $v_{max_{tc}}$ on that
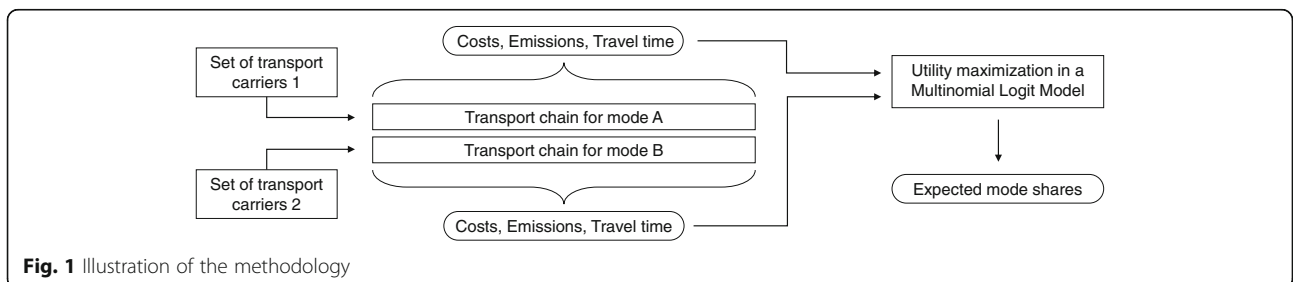

Fig. 1 Illustration of the methodology

link, the link's maximum speed v_l, and a transport carrier specific standstill time $stst_{tc}$ to model congestion:

$$TD(v_l, v_{maxtc}, d_l, stst_{tc}) = \ min\left\{\frac{d_l}{v_{maxtc}}, \frac{d_l}{v_l}\right\} + stst_{tc}*d_l \quad (4)$$

The energy cost is a product of energy demand *ED*, d_l and the fuel price function $FP(fuel_{tc}, country_l)$. The latter, as well as the infrastructure cost function $INFC(country_l)$ and fuel emissions function $FEM(fuel_{tc}, country_l)$, maps country and fuel dependent values in the input data. *ED* of all modes' possible transport vehicles is calculated with a linearized function (5). It is two-dimensionally dependent on the velocity v_l and the load (as a product of transport units $units_l$ and their density ρ), with $ed_{max,0tc}$ as intercept at maximum velocity and zero load [kWh/km], μ_{tc} as slope of gross vehicle weight [kWh/(kg*km)] and λ_{tc} as slope of the difference between v_l and $v_{max_{tc}}$ [kWh/((km/h)*km)]:

$$\begin{aligned} ED&\left(v_l, units_l*\rho, ed_{max,0_{tc}}, \mu_{tc}, \lambda_{tc}, v_{max_{tc}}\right) \\ &= ed_{max,0_{tc}} + \mu_{tc}*units_l*\rho + \lambda_{tc}*(v_{max_{tc}} - v_l) \end{aligned} \quad (5)$$

Emissions *EM* (2) depend on the fuel demand of the transport carrier on that link or the transhipment process. The variable vehicle driving emissions are calculated in the same way as the fuel costs, just mapping emission data instead of prices. Variable emissions in case of a transhipment link em_{trans_l} are dependent on $loading_l$ and $unloading_l$.

For costs and emissions, each link's value is multiplied with the quantity of transport carriers on that link q_{tc_l} to model situations where several vehicles are needed to satisfy a given transport demand. q_{tc_l} is the round-up ratio of the difference between loading and unloading until that link in the transport chain and the maximum load ($maxload_{tc}$ multiplied by maximum load factor τ_{tc}) of that link's transport carrier (6):

$$q_{tc_l} = \left\lceil \frac{\sum_{(i=1)}^{l} loading_i - unloading_i}{maxload_{tc}*\tau_{tc}} \right\rceil \quad (6)$$

Transport time *T* (3) is calculated as a sum of the time demand for transport carriers *TD* (4) and both, a fix and variable transhipment time for every transhipment link ($t_{trans-fix_l}$ and $t_{trans-var_l}$, the latter being dependent on the number of loaded and unloaded transport units).

2.2 Mode choice modelling
The implemented mode choice model is a reproduction of the decision maker's choice behaviour within a discrete choice set (discrete, behavioural model) which is derived from random utility theory. Logit models have been best practice in discrete choice modelling for decades, especially in transport literature [30–32]. They are subject to several assumptions (see [33, 34]):

- every individual is a rational decision maker maximizing the utility of his or her choices;
- decision maker *i* considers mutually exclusive alternatives, which make up his or her choice set I^i;
- each alternative *j* has a perceived utility U_j^i, based on microeconomic consumer theory;
- U_j^i depends on a number of measurable attributes X_j^i (as a vector) and
- U_j^i is not known with certainty by an external observer, which is why it is split into a systematic utility V_j^i and a random residual ε_j^i considering unobservable errors: $U_j^i = V_j^i + \varepsilon_j^i \quad \forall j \in I^i$

In this model, the individual shippers are aggregated to one generic decision maker, which is why the index *i* is not required in all upcoming mathematical descriptions. Random residuals comprise all influences of decision making that are not addressed in the systematic utility and other errors in the analytical expression of performance attributes, errors in the input data, errors due to omitted performance attributes and errors occurring due to the aggregation of decision makers.

The probability that the utility of alternative *j*, U_j, is greater than all the other alternatives in the choice set *I* can be expressed as follows (7):

$$p[j/I] = P_j = Pr[U_j > U_k \ \forall k \neq j, \ k \in I] \quad (7)$$

An appropriate statistical model must be applied to estimate the perceived utility of the decision maker. The simplest and most common utilization of random utility theory is represented by the Multinomial Logit model (MNL). It is assumed that random residuals ε_j are independently and identically distributed according to a Gumbel random variable of zero mean and parameter θ, which leads to the following expression for the mode choice probability (8):

$$P_j = \frac{\exp\left(\frac{V_j}{\theta}\right)}{\sum_{j=1}^{m} \exp\left(\frac{V_j}{\theta}\right)} \quad (8)$$

2.3 Model calibration
The perceived utility must be calculated, to estimate a modal split. Hence, a vector β is defined consisting of a cost sensitivity of 1 (i.e. neutral perception of cost), a value of time (VoT) in EUR/(h*t) and an emissions penalty in EUR/tCO$_2$eq (e.g. CO$_2$-tax to internalise external cost from GHG emissions). The VoT describes the decision maker's appreciation for the acceleration of goods. It positively relates to the weight-specific value, interest rates and deterioration of goods and is independent of

distance and transport mode [5]. Most commonly, data is gathered with Stated Preference surveys and evaluated in a Logit model [35, 36]. β is multiplied with the performance attributes *C*, *EM* and *T* to bring them on a common scale (EUR per transport unit), wherefore the VoT is rescaled to transport units under use of the scenario-specific unit density. *C*, *EM* and *T* are considered as unit-specific values because shipment sizes vary between transport carriers and the decision-maker considers load-specific performance values.

Parameter θ is a control variable for the selectivity of the mode share estimation results, i.e. the variance of the probability distribution [33]. Studies that gather micro data for discrete choice modelling usually estimate the perceived utility U_j^i directly, making θ obsolete (see [37, 38]). The present study uses literature values for β to compute V_j which requires the calibration of θ depending on possible error sources described in the previous subsection. We find a value of 0.5 for this study's model structure based on the simulation of conventional intermodal rail-road and unimodal road transport relations on distances ranging from 100 to 1000 km in Germany.

While it is intended to model the full internal cost and time of a transport chain, emissions calculation does not happen according to a life-cycle analysis. Vehicle, infrastructure and terminal building emissions are excluded from all components and only well-to-wheel CO_2eq emissions from fuel consumption (including well-to-tank and tank-to-wheel) are accounted. Costs of transport exclude logistics operations (other than cargo carriage), margins and business overheads of any service providers above the level of carriers. The expression "fuel" includes electricity in this paper.

3 European scenario 2030

The idea behind the NGT CARGO concept is a dense European HSR network with block trains rushing from one hub to another and single wagons driving to and being loaded at external logistic sidings autonomously (powered by an internal energy storage and motor). This could facilitate a widespread modal shift from road to rail. Even though we model with predicted data for the year 2030 it is improbable that such a network exists until then. Nevertheless, certain European transport corridors show high transport volumes of LDHV goods (mainly transported via road today and in the projected future) and thus, potential for a first application of the NGT CARGO concept worth investigating.

The market analysis and the operating concept as well as scheduling used for definition of this scenario's transport corridor (Madrid to Vienna) was conducted by

Knitschky et al. [39] and Schumann et al. [15]. It is based on the traffic forecast data of the German Federal Transport Infrastructure Plan 2030 (German: Verkehrsverflechtungsprognose 2030; VP2030; [10]). It contains international traffic originating from or transiting through Germany as well as inner-German traffic on NUTS-3 level resolution [10].[1] The selected cargo types are LDHV goods on euro pool pallets or in unit load devices with a specific weight of 350 kg per loading unit (ρ). The whole transport demand considered here is projected to be satisfied by lorries in the VP2030. Figure 2 depicts the hubs along the transport corridor and the corresponding loading and unloading volumes per day. As can be seen, the eastbound transport volume roughly corresponds to the westbound volume which is important for vehicle and terminal productivity. For sake of simplicity, pre- and on-carriage are excluded from calculations.

In the European scenario, trains use high-speed railway lines expected to be available in 2030[2] with permissible maximum operating speeds along the transport corridor [15].

Lorries use national highways with an average speed of 70 km/h, which is slightly faster than average values because of long distances between hubs. In 2030, lorries are still modelled diesel-powered with emission class EURO VI because this drivetrain is assumed to represent the highest share in the heavy-duty road vehicle fleet (see [42]). The transhipment in each hub is assumed to cost 60 EUR per full lorry load and take 1 h for a fully loaded lorry.

The transhipment system of the HSRF concept is based on a new terminal structure outside the cities being able to unload and reload an entire block train within 5 min. Emissions are assumed to be 0.2 kg CO_2eq per pallet (due to high degree of automation and electrification). The costs are assumed to be roughly the double of conventional road-rail terminals with handling volumes of 20,000 to 100,000 TEU per year (see [43]). Thus, we assume loading or unloading costs to be 10 EUR per pallet.

The track access charge systems for railways in Europe are highly diverse and dependent on many boundary conditions [44–46]. For country specific track charges we differentiate between two scenarios, based on the current network statements of the respective countries for freight

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[1]The data set was provided for research purposes. The file format is an origin-destination freight transport matrix for the 2030 forecast and is based on the approach of Knitschky et al. [39] and Schumann et al. [15].

[2]Montpellier - Avignon: already in operation; Lyon – Dijon (Rhin-Rhône Sud): slightly delayed; Mülhausen – Karlsruhe: delayed, speed increase between Offenburg and Freiburg planned until 2030 [40]; Stuttgart – Ulm: under construction, start of operation planned for 2025 [41].

Fig. 2 Transport demand of LDHV goods on the transport corridor ES - AT and vice versa
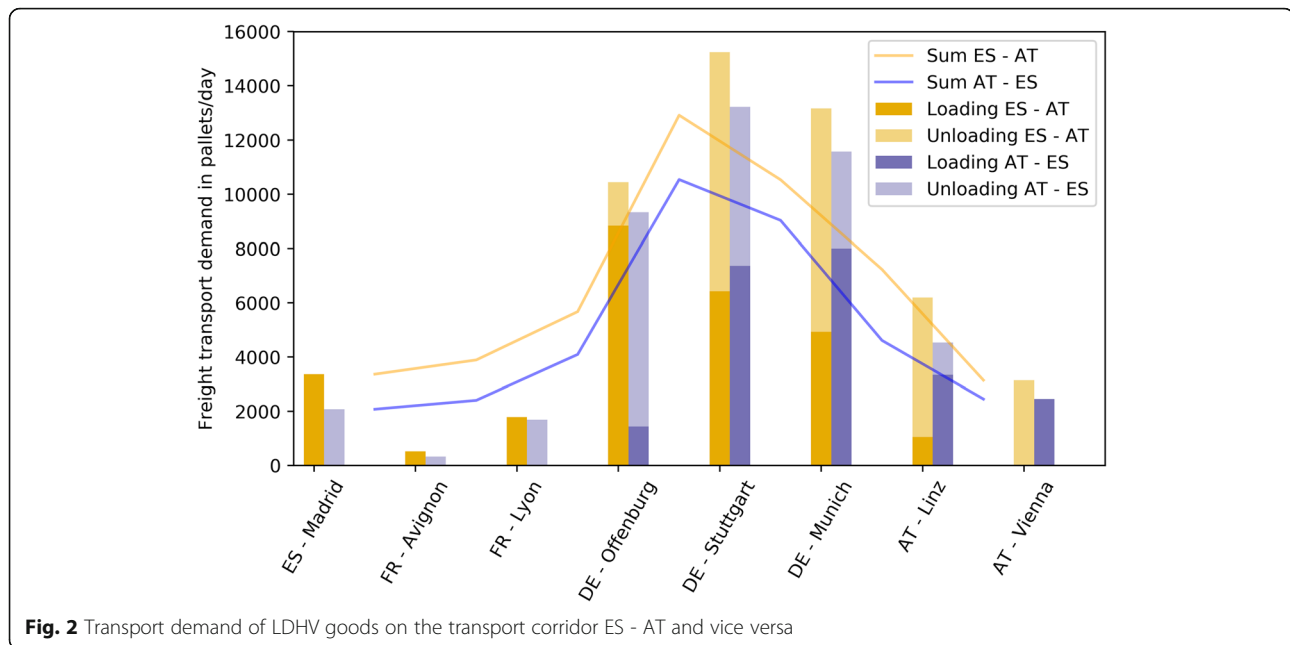
Table 1 Country specific parameters: prices and emissions for 2030

Country	Diesel[a] [EUR/kWh]	Electricity[b] [EUR/kWh]	Traction electricity emissions[c] [gCO2eq/kWh]	Road fees[d] [EUR/km]	Track charges conventional rail freight[e] [EUR/train km]	Track charges HSRF[e] [EUR/ train km]
Austria	0.133	0.10	138.6	0.40	17.54	19.79
France	0.159	0.09	70.6	0.22	2.12	23.80
Germany	0.139	0.13	476.3	0.13	6.54	17.11
Spain	0.133	0.11	254.5	0.15	0.25	9.17

[a] https://www.globalpetrolprices.com/diesel_prices [accessed at 1st November 2019], 10% estimated price increase by 2030, WtW diesel emissions: 325.8 gCO2eq/ kWh following EN16258 specifications; [b] Prices for non-households from Eurostat (2019), no price change by 2030 even though nominal prices may decrease (see [47–49]); [c] Rail electricity mix at pantograph, emissions data from Ifeu et al. [50], 65% estimated emissions reduction by 2030 compared to 1990; [d] If existent, the latest road fees are retrieved from national information in the internet. Otherwise, from BVU et al. [51]; [e] Based on the current network statements of the respective country for freight and long-distance passenger transport, adjusted to 2030 values. For detailed information see Additional file 1 (description of the calculated country specific track charges for 2030)

Table 2 Vehicle specifications

Parameter	HSRF train[c]	Lorry with semi-trailer[d]
Vehicle design	Block train with two locomotives and ten single wagons in between	40 t max gross weight, Euro VI emission class, 4+ axles
Max Load [pallets]	900	34
Max speed [km/h]	350	90
Vehicle costs [1000 EUR]	54,800[a]	70
Mileage yearly [1000 km/a]	1,008	135
Lifetime [a]	10	6
Personnel costs [EUR/h]	8[b]	23.81
Maintenance and other costs [EUR/ km]	3	0.21
Fuel	Electricity	Diesel
$ed_{max,\ 0tc}$ [kWh/km]	38.40	2.12
μ_{tc} [kWh/km/kg]	$1.24*10^{-5}$	$4.06*10^{-5}$
λ_{tc} [kWh/km/(km/h)]	−0.1013	0

[a]Vehicle cost estimation based on ICE 3/Velaro, with comparable technical properties, assuming a cost increase factor of 2 for chassis, power supply, propulsion, on-board control, factor 1.5 for car body, assembly and acceptance, factor 0.6 for vehicle equipment; [b] Remote-operation 10 trains/person; [c] NGT CARGO specification book and operational concept, fuel demand calculated from own simulations; [d] data from BVU et al. [51], vehicle cost data from Lastauto Omnibus-Katalog [53]: average value of six 18-ton semi-trucks plus 20,000 EUR for the trailer, costs inflation-adjusted to 2030 (annual growth 1.5%), the price is based on a 50% write-down and resell value rate, as it can be found in other sources, fuel demand calculated from fuel station bills for long haul driving cycles [54]

and long-distance passenger transport (Table 1). The calculated track charges consider line and train type, gross weight, velocity, international charges and supplements for congested rail infrastructure. As a simplification we excluded service charges, low-speed and delay penalties and noise bonus. Terminal service cost we calculated separately. We assume a country specific increase of track access charges by 2030 based on the changes to previous years (see Additional file 1).

The employed VoT is taken from a study by Significance et al. [52] with Stated Preference data from the Netherlands. They find 3.87 EUR/(h∗t)[3] as average VoT travel savings for non-container road transport with loads from 2 to 15 t (in average 8 t), which matches the definition of LDHV goods in this paper: Average weight of 350 kg/pallet and average value of 2,937 EUR/t (see [15]).

The expected mode share, emissions and costs are further analysed under different parameter variations (track charges, velocity, unit handling, VoT, CO_2-tax). All that combined yields an optimistic parameter set that includes a VoT of 5 EUR/(h∗t), a CO_2-tax of 100 EUR/tCO_2eq, HSRF track charges of 8 EUR/km, double road fees, and unit handling costs of 5 EUR per pallet.

Vehicle specifications and country-specific emission data, prices for fuels and infrastructure charges for rail and road transport that are considered in this paper can be found in Tables 1 and 2.

4 Results

All results are given in units per day to enable the comparison of different transport alternatives and assess the real market potential at the same time. In 2030, 93 to 380 diesel-powered lorries are expected to travel along different parts of the modelled transport corridor to satisfy the given freight transport demand, emitting 411 tCO_2eq per day in sum. If all that freight transport demand was satisfied by a HSRF concept, four to fifteen block trains would emit 88 tCO_2eq per day with the expected electricity mix.

The results for the baseline parameter set show that total cost of HSRF is about 70% higher than these of the conventional lorry (Table 3). Main cost drivers are unit handling in terminals and railway track charges while the largest cost components of the lorry (fuel and personnel costs) play a minor role for HSRF. Along the route, load factors from 86 to 98% are realized with the modelled transport demand. The distance-weighted average is 89% which generates average costs without terminal activities under the level of road transport (0.10 EUR/tkm). This comparably high load factor results from small loading units and high handling flexibility of the multimodal train

concept. It indicates higher competitiveness to road transport compared to conventional intermodal rail-road transport. The lorry's total transport chain GHG emissions are 4.7 times higher than those of the HSRF train. The latter uses electric traction with low carbon intensities, continuing the current trend towards renewable electricity generation in Europe. Furthermore, it features energy efficient high-speed operation due to highly efficient rolling material, lightweight design and low aerodynamic drag. The average HSRF train speed declines on the route from Madrid to Vienna because of a less extensive HSR network in Germany and Austria.

Variations of the scenario parameters yield strongly varying results. The application of freight service track charges with a reduction of maximum operating speed to 160 km/h causes a significant decrease of specific costs due to lower railway track charges and electricity costs (see Fig. 3). Moreover, a maximum operating speed of 160 km/h reduces average emissions of the HSRF concept from 15.0 to 11.1 gCO_2eq/tkm, which is 6.4 times less than the lorry's emissions.

Likewise, the application of freight train track charges shows a positive effect on the expected mode share, even though the average speed drops from 135 km/h to 107 km/h. The reaction to higher VoTs is very positive (reaching a crucial mode share of 50%) while the expected mode share for lower VoTs still lies slightly over the baseline value (Fig. 4). Similar results show the reduction of HSRF passenger track charges to 8 EUR/km, which is especially high in combination with doubling of road fees for lorries. The most effective single-measure is reducing unit handling costs to 5 EUR per pallet. A CO_2-tax of 100 EUR/tCO_2eq shows only minor effect. In the optimistic case, 62% of the lorries could be replaced by the HSRF concept. This would reduce CO_2eq emissions to roughly 200 t per day in 2030.

5 Discussion and conclusions

The purpose of this paper is to draw pathways for the introduction of a HSRF concept in Europe, in particular to estimate the modal split between HSRF and conventional road transport and elaborate on influential factors. Costs, emissions and time were evaluated with the focus on LDHV goods which are currently predominantly carried by road vehicles but could be shifted to rail in 2030. For this, a mode choice model with an integrated transport chain performance calculation tool was developed.

The results show that multimodal unit handling expenses are an essential cost factor. Assumed a cost-effective transhipment concept, the expected mode share exceeds 50%, outperforming road transport in all three target values of this paper. Islam and Zunder [18], Jackson et al. [16], and Zunder and Islam [14] also find that unit handling is crucial for effective and competitive rail freight transport, especially in the LDHV goods segment.

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[3]Inflation-adjusted with historic values up to 2020 and 1.5%/a onwards.

Table 3 Simulation results for European scenario 2030 with baseline parameter setting
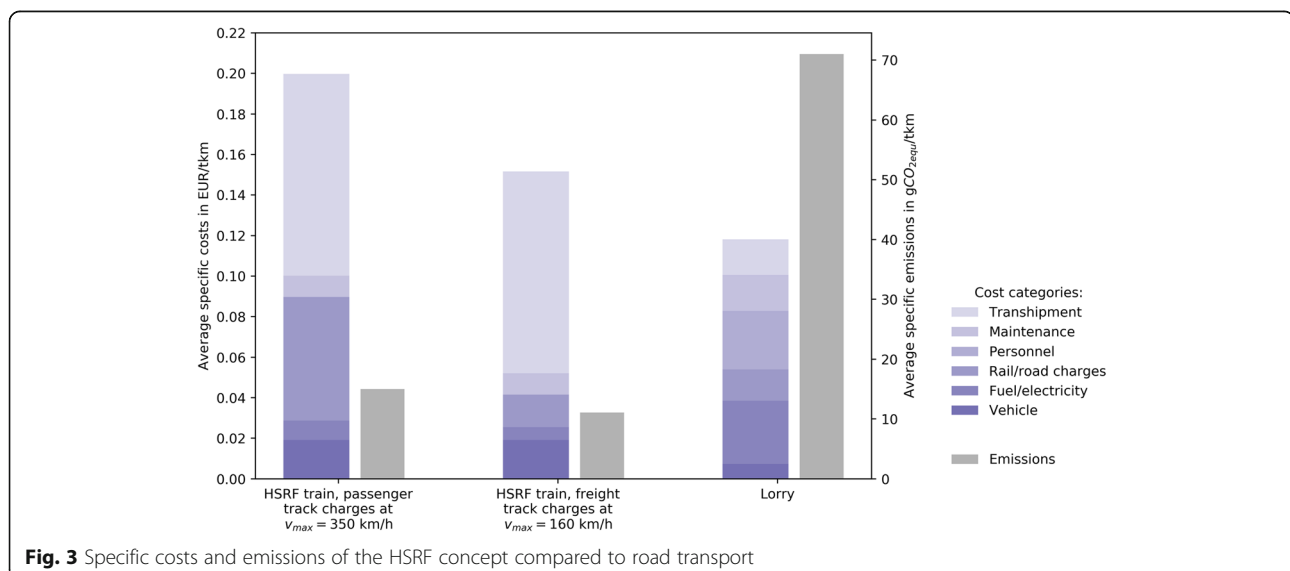
|	HSRF train	Lorry with semi-trailer
Mode share	41.9%	58.1%
Total cost [EUR/d]	1,164,402	684,285
Total emissions [tCO$_2$eq/d]	87.6	410.9
Average speed [km/h]	134.9	57.6
Specific costs [EUR/tkm]	0.20	0.12
Specific emissions [gCO$_2$eq/tkm]	15.0	71.0
Cost share of transhipment	49.8%	15.0%
Cost share infrastructure charges	30.5%	13.2
Time share of transhipment	35.3%	17.6%
Specific rail/road charges [EUR/tkm]	0.061	0.016

Despite the technical implementation, the most effective policy instrument to support HSRF transport in Europe is the design of rail track access charges and road fees. Currently, there is no comprehensive HSRF operation in Europe which is why there are no track charges to be deducted for this study. However, assuming national passenger service HSR track charges, the average rail charges per tkm are 3.9 times higher than the road counterpart today. An adjustment is deemed important to create a level playing field in LDHV goods transport. Moreover, road freight transport externalities are reasonably higher than those of the rail mode and there should be higher aspirations of internalizing transport's external costs (see [55] for reference values).

The replacement of road transport with the proposed HSRF concept in the LDHV goods segment for a trans-European transport corridor could save up to 79% GHG emissions. Even though solely on the simulated transport corridor every day, several hundred tons of GHG emissions could be saved, a CO$_2$-tax of 100 EUR/tCO$_2$eq would have little effect on the expected modal split. This is due to comparably low emissions per transport unit. The monetarized GHG emissions penalty represents 5.7% of the transport costs in the case of lorry operation and 0.7% for the HSRF train. CO$_2$ emission penalties on a higher scale are not considered realistic for 2030 under current policies (see [56] for comparison).

Lower maximum speeds of the HSRF concept correspond to lower GHG emissions from electricity consumption while expected mode shares are dependent on the VoT and the track access charges applied. One core element of the examined HSRF concept is the free integration of freight and passenger transport which leads to more efficient utilization of the rail network and lower infrastructure costs (see [14]). Maximum speeds of up to 350 km/h make the full operational inclusion possible but result in lower expected mode share than operation with a maximum of 160 km/h. The latter represents the threshold for application of (higher) passenger service HSR track charges in this paper and the maximum operating speed of regional passenger services. Lower speeds respond less

Fig. 3 Specific costs and emissions of the HSRF concept compared to road transport

Fig. 4 Sensitivity of mode share and specific costs for the HSRF concept to distinct parameter variations
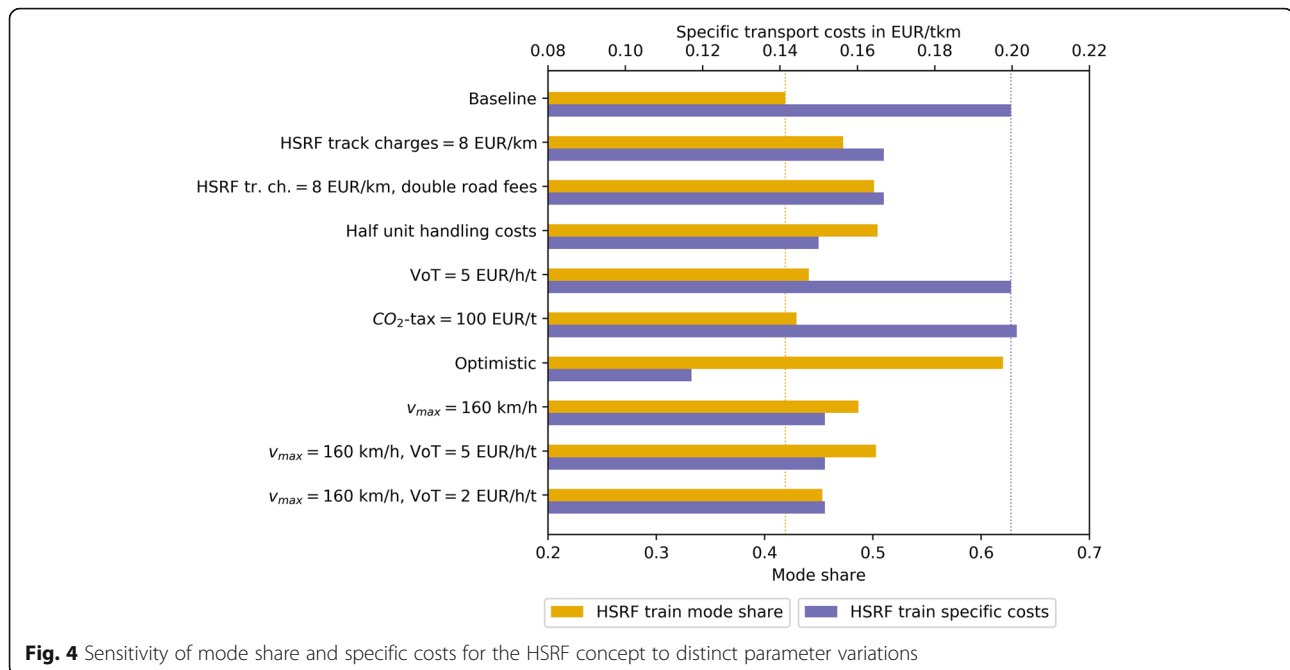
negatively to a lower VoT and more positive to a higher VoT than the baseline parameter setting. This implies the applicability to a wider market segment (still within LDHV goods). Moreover, vehicle and maintenance costs could decrease for lower performance ratings. However, they make only a small share of specific transport costs due to high productivity of the rolling stock on this transport relation (i.e. 86 to 98% load factor compared to 70 to 85% in average for rail freight [57]. Overall, the operational speed needs to be adjusted to the transport corridor's utilization, the applied track charges, and the respective types of transported goods (VoT) which requires higher flexibility than current rail freight transport services.

An innovative multimodal HSRF concept could replace road freight transport in the LDHV market segment to a certain extent. The resulting mode share depends on transport policy actions, an effective implementation of HSRF solutions and – most notably – the eco-awareness of decision makers. To meet the goals of the Paris Agreements for the freight transport sector, there must be the ambition for system change with the objective of reducing the sector's GHG emissions and other external costs. For further research, the cost influence of multimodal road-rail transhipment terminals for different layouts in the LDHV segment and the influence of network effects – especially on the HSRF concept – should be considered in more detail.

6 Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12544-020-00453-3.

> **Additional file 1.** Description of the calculated country specific track charges for 2030.

Authors' contributions
MB conceived and designed this paper based on the results of MA who particular developed the methodology within the framework of his master thesis. JW contributed to the methodology. MB and MA collected, processed and evaluated the data. MA and MB carried out the essential revisions. All authors read and approved the final manuscript.

Availability of data and materials
The data used to calculate the 2030 transport demand of LDHV goods on the transport corridor ES - AT and vice versa as well as the choice of good categories for this paper's definition of LDHV goods is based on [10]. This dataset is not publicly available because the provision and use of more in-depth (micro-) data from BMVI surveys for scientific purposes is subject to further requirements and requires a separate agreement, are available from the corresponding author on reasonable request. The authors further declare that all other data generated or analysed during this study are included in this published article.

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

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