Uniform ontworpen Europees HSL-netwerk, impact voor lijnvoering, ticketprijzen en governance strategie

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Samenvatting

Hogesnelheidstreinen (HST) worden vaak gezien als een veelbelovend alternatief voor langeafstandsvervoer door de lucht en over de weg door hun potentiele milieuvoordelen, het concurrerende serviceniveau en het potentiele comfort. Door een gebrek aan kennis over het ontwerp van HST-verbindingen vanuit netwerk perspectief, en door nationale- en bedrijfsbelangen, is er echter nog geen écht Europees HST-netwerk. Dit leidt tot een suboptimale situatie voor reizigers, spoorwegbedrijven en de maatschappij.

In dit onderzoek is voor het eerst het klassieke 'Transit Network Design and Frequency Setting Problem' (TNDFSP) toegpast in een HST-omgeving. In een dergelijk probleem wordt de ideale selectie van lijnen en bijbehorende frequenties gezocht in een gegeven infrastructuur. Dit onderzoek ontwikkelde een nieuw generiek model voor deze HST-omgeving tezamen met een specifiek oplossingsalgoritme, welke vervolgens geparametriseerd werden voor de casus van het Europees continet. Door de huidige situatie te benaderen; door het relatieve belang van voertuig-, passagiers- en lijnontwerpvariabelen te analyseren; door het evalueren van prijsstellings- en beleidsstrategieën; en door tot slot het voorstellen van verbeterde uitgangspunten voor het ontwerp van HST-netwerken, was het mogelijk om de effecten van een versterkt ontwerp te beoordelen.

Uit de experimenten bleek dat de voordelen voor alle belanghebbenden tegelijkertijd konden worden versterkt door gecentraliseerd ontwerp en beleid, het internaliseren van externe kosten en het toepassen van strategisch gekozen ontwerpvariabelen. Hierdoor kon het geschatte marktaandeel groeien van 14,7 % naar 29,9 %, tegelijkertijd verbeterde ook de maatschappelijke kosten-batenverhouding met 20,0 %. De overheidsinvesteringen tussen de meest voordelige naar de meest uitgebreide oplossing bedragen jaarlijks €2,2 miljard, maar komen terug met een positieve rate of return van 1,8 keer in de gecombineerde gebruikers- en maatschappelijke voordelen. Ook demonstreerde het model de noodzaak om omrijdende en daarmee onrendabele passagiers uit het systeem te weren. Ten slotte kwam ook het belang van betere samenwerking naar voren uit de sterke netwerkintegratie met overlappende en grensoverschrijdende routes van aanzienlijke lengte, de tegenstelling tussen nationale en internationale belangen en het hoge aantal kritische infrastructurele elementen.

In breder perspectief toonde deze studie de mogelijkheid aan om de TNDFSP toe te passen in een HST-omgeving, wat nieuwe kansen opent voor een sterker begrip van het ontwerp van netwerken voor hogesnelheidstreinen. Voordelen in duurzaamheid en mobiliteit kunnen bereikt worden door verbeterde ontwerpkeuzes, internalisering van externe kosten en het beperken van concurrentie binnen de spoorwegmarkt en nationale soevereiniteit; Toekomstig onderzoek zou verder kunnen gaan door de aanleg van infrastructuur te integreren, plannings- of operationele aspecten mee te nemen, verschillende casestudies te beoordelen of door nieuwe technologieën te introduceren.

1. Introduction

Over the last century, long-distance travel has become more and more common (The World Bank, 2020). Bringing many advantages by enhanced mobility, it also comes at the cost of externalities, such as the depletion of finite natural resources, noise pollution and the contribution to climate change (Janic, 1999). Frequently, High-Speed Rail is considered as a promising alternative for short-haul flights (<1500 km) and long-distance car travel (>200 km), by providing competitive services against fewer environmental disadvantages (Albalate and Bel, 2012;). With this knowledge, great encouragements and investments have been made for a European HSR network (European commission, 2020).

Despite the combination of seemingly favourable circumstances, no real European HSR network has been realised yet. The infrastructure is largely existing, but the current network is a patchwork of poorly connected sub-networks without a good cross-border coordination (European Court of Auditors, 2018). Two main underlying problems cause this suboptimal state: (1) a lack of knowledge on design of line configurations for High-Speed Rail from a network perspective and (2) a reduced network integration due to prioritisation of national and railway company interests. (Rli, 2020). This study initially focuses on the first, but with that also gains insights into the second. To determine how these problems can be addressed, a quantitative study on the line configurations of HSR networks, based on the 'Transit Network Design and Frequency Setting Problem' (TNDFSP) (Guihaire and Hao, 2008), was performed in this study. This research is the first attempt to transform and solve this problem, that is typically used in conventional transit systems, into an HSR setting. By generically defining this HSR-adapted problem, formulating a novel solution algorithm and modelling the case-specific European environment, this paper aims to gain insights into HSR network design. This, to ultimately answer the main research question:

'"To what extent can the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies and how would such networks look like?"'

The remainder of this paper is organised in the following structure: section 2 reviews a brief overview of relevant studies and their link to the HSR environment. Following, an elaboration of the exact problem, the methods used to solve this, the parameterisation of the European case and model implementation are discussed in section 3. Continuing, section 4 presents the results of the performed simulations and the extrapolated lessons of these, after which the final conclusions are drawn in section 5.

2. Literature

Public transport systems are often advocated for due to their potential mobility and environmental benefits. However, to reach an effective state for such systems, a balance has to be found between the quality of service for users, the costs for operators and the impact on the system's surroundings (Guihaire and Hao, 2008; Farahani et al., 2013). The sections below perform an assessment of the literature in the field of strategic transit design. This, to identify available techniques, their potential for HSR and the challenges.

2.1 Transit Network Design and Frequency Setting Problem for HSR

Ideally, all aspects of a transit network would be designed simultaneously. However, due to the highly complex working environment and stakeholder interests, the problem is frequently divided into smaller sub-problems. The problems that quantitatively describe these problems can be encompassed under the name 'Transit Network Planning Problem' (TNPP) (Ibarra-Rojas et al., 2015). Guihaire and Hao (2008) defined a framework of combined TNPP-problems. The topic of this specific study on centrally designed HSR line configurations, can be classified in the category of 'Transit Network Design and Frequency Setting Problems' (TNDFSP). The TNDFSP combines a (1) *'Design Problem'* (set of lines, consisting of terminal stations and intermediate stops) with a (2) *'Frequency Setting Problem'* (that finds adequate time-specific frequencies) for a given demand. The resulting output of the two combined problems consists of a *'Line Plan'* and their associated *'Frequencies'*. Together, they form the *'Line Configuration'* (Kepaptsoglou and Karlaftis, 2009; Schöbel, 2012). No studies applying this problem to HSR were found. To learn about this, the sections below perform an assessment of existing TNDFSP studies for conventional transit and other relevant HSR studies.

Objectives: As the TNDFSP makes a trade-off in the interests of multiple stakeholders, it is classified as a multi-objective problem. Typically, transit planning has two main partners involved: the operator wishing to minimise its costs and the user desiring a maximisation of its benefits (e.g. travel time, costs) (López-Ramos, 2014) Frequently, studies expand these stakeholder interests by incorporating a broader set of goals, such as the minimisation of external costs, transfers and fuel consumption, or the maximisation of capacity or total (societal) welfare.

Decision Variables: In general, two main decision variables are used for the TNDFSP: the (1) '*line selection*' and (2) '*line frequencies*', although sometimes expanded by the '*vehicle type*' (Kepaptsoglou and Karlaftis, 2009). However, implicitly many more decision variables are taken into account, as the selection of a specific line comes with its own characteristics, such as covered lengths, stop locations, directness or the lack of that (Fan and Machemehl, 2008).

Network Characteristics: A TNDFSP network consist of '*vertices*' (stations), '*edges*' (direct connections between vertices), '*lines*' (services on connected edges) and '*paths*' (passenger between two vertices following lines) (Schöbel, 2012). Most network optimization studies in the field of HSR (e.g. Lovett et al. (2013)) use a realistic irregular (grid) structure, as the spatial geography on longer distances typically follows an irregular pattern when compared to urban regions. The size of these structures remains relatively limited, reaching a maximum of 10 vertices. Following this, (Jong et al., 2012) acknowledges the infrastructural limitations of (high-speed) rail infrastructure by combining a strategic frequency setting problem with a tactical timetabling problem.

Demand Characteristics: From literature, three main aspects of demand modelling in TNDFSPs are found. Firstly (1), two distinctive '*Spatial patterns*' are identified: a '*one-to-many*' demand pattern (focus is at one vertex, e.g. Chien and Schonfeld (1998)) and a '*many-to-many*' demand pattern (emphasising flows on a network scale, e.g. Hassan et al. (2019). Secondly (2), the *'time scope'* varies between years for the construction of infrastructure and minutes for tactical and operational problems (Farahani et al., 2013; Rojas et al., 2015). Finally (3), differences in '*dynamic demand responses*' are observed. These can be subdivided into '*fixed or elastic total demand*' (when considering generation effects) and '*fixed or elastic mode specific demand*' (when evaluating mode sub-stitution) For a TNDFSP in the HSR domain on the European continent, it is considered that '*many-to-many*' demand pattern and a longer '*time-scope*' are required. Furthermore, considering '*elastic demand patterns*' could strongly increase the accuracy. Many of TNDFSPs for conventional transit systems assume demand to be generated by residential zones. For long-distance transport, the generation must be sought in other factors.

Constraints: Imposing constraints on optimisation problem ensures realistic solutions, and reduces the computational requirements. Schöbel (2012) identified constraints which mainly concern budget, capacity and connectivity requirements. López-Ramos (2014) also recognises express services, the inviolability of existing lines and time horizon to finish tasks. Additionally, Zhao and Zeng (2006) focusses on classical bus systems and finds line design constraints, such as directness, length, shape, and load factor requirements. Rail transport is characterized by its infrastructure and the subsequent requirements. This provides constraints like physical interoperability and safety systems, more complex station or edge capacities and difficulties in overtaking as well as political factors (Yue et al., 2016). However, their complicated nature makes that they cannot always be quantified. This research emphasizes on line design, rather than operational constraints.

2.2 Solution Strategies

TNDFSPs are seen as relatively complex problems. In Fan and Machemehl (2004), six main factors of complexity were identified. Schöbel, (2012) observes that this problem often has an application-driven character, results in a variety of problem formulations and solution approaches. Kepaptsoglou and Karlaftis (2009) defines the two most fundamental strategies as the '*Line Generation & Configuration*' method (set of candidate lines is generated, a sub-selection is selected for the final network) and the '*Line Construction & Improvement*' method (starts with an initial line plan and step-wise improved by altering lines). The processes to solve these problems follow either '*conventional techniques*' (analytical and mathematical programming) or '*heuristic techniques*' (heuristics and meta-heuristics) (Kepaptsoglou and Karlaftis, 2009; poulou et al., 2019). The application of conventional techniques is generally considered less suitable. For the analytical options, this follows from the problem being NPhard and the results being opaque. For the mathematical programming, this follows from the inability of realistically representing the structure of lines (Iliopoulou et al., 2019).

Concerning the heuristic techniques, it is seen that a variety of procedures are applied. Regular heuristics mostly use '*constructive strategies*' (skeleton, end-node assignment and network), which are applied either in successive or simultaneous order. In meta-heuristics, a threefold division is found: '*single-solution*' (e.g. Tabu Search, Simulated Annealing or GRASP), '*population based*' (e.g. Evolutionary algorithms or swarm intelligence such as Ant or Bee colonies) and '*hybrid*' forms Iliopoulou et al. (2019). The wide variety of applied techniques indicates the importance of customised approaches.

3. Methodology

The first step (1) was to define a customised version of the TNDFSP, the second step (2) was to formulate a novel heuristic that strategically searches the solution space for strong performing results in a reasonable time. The final step (3), was to parameterize the newly described problem for the European case study. By implementing the previously described model and constructing multiple experiments (4), to simulate multiple scenarios.

Modelling choices were made to match the strategic objective and simplify the problem. The continuous state perspective is such that the expenses (infrastructure construction or vehicle acquisition) are not considered. The associated time-span of this continuous state equals one operational day. In this state, all costs components are considered relative to a situation with no HSR. The following modelling assumptions have been made: the total demand is fixed (no generation) mode-specific demand is elastic, based on level of service and assigned assuming a stochastic uncongested user equilibrium; the network is symmetric for each OD-pair (demand, level of service); vehicles of the same mode are homogeneous and vehicles do not interact whatsoever; no operational strategies (e.g. deadheading or shortturning) are considered. HSR infrastructure is interoperable and incapacitated. HSR allows for a maximum of two transfers per path; air travel assumes direct trips only.

3.1 Problem definition

The network is expressed as an undirected and incomplete *'graph'*, composed of a finite set of cities represented as *'vertices'* and a finite set of connections between these cities represented as *'edges'*. Furthermore, different ways of transport are distinguished by *'modes'*. A *'line'* is defined as a service that is a sequence of directly connected vertices. Combining multiple of these lines gives a *'set of lines'*. Passengers travelling through this network using a single line follow a *'direct path'* and passengers with a transfer follow a *'transfer path'*. Together, paths form the *'set of paths'*, where each pair of vertices has only one such path. This study follows the two main decision variables of a typical TNDFSP: the 'set of lines', definition of selection of lines to be active, and the associated 'frequencies'.

The objective is the minimization of the weighted costs as experienced by three main stakeholders: *'Users', 'Operator' and 'Society'.* The weights reflect the pricing policy trade-offs. The user costs follow from the (monetized) time spent on travelling (Value of Time, indicated as *VoT*). Thus the user's objective is to minimize its travel costs. A trip (mode-dependent) can consist of five elements: *'acces'*, *'waiting*, *'in-vehicle'*, *'transfer'* and *'egress'*. Overall user costs are sum of passengers that spend a time at a specific point. The operator runs the HSR network, with the objective to minimize the costs. The main costs components are covered in the (1) '*operational*' and (2) '*maintenance*' expenses, expressed in cost per seat-kilometre. The societal costs follow from indirect effects that, not paid by user or operator, but rather by society. Internalisation is done with the combination of passenger-flows and mode-specific overall external costs per pax-km.

The objective is constraint in several manners to ensure feasible results and restrict the solution space (and computational burden). The constraints are divided into three categories: *'Line Design', 'Line Frequency'* and *'Passenger path'* constraints.

- Line design constraints are: '*minimum line length*' and '*minimum number of stops*' (prevent nesting with conventional rail and assure a network function); the '*round trip time*' (all trains should be able to return within one operational day); '*line symmetry*' (lines should be identical in both directions); '*infrastructural and geographical detour*' (prevent strong detours and reduce computation time).
- Line frequency constraints safeguard feasible solution rather than user and operator friendly timetables due to the strategic focus of the study. These are: '*minimum frequency*' (non-negativity and prevents ghost lines, active lines without trains); '*integer frequency*' (no partial trains); '*frequency symmetry*' (guarantees the continuity of trains by making sure the frequency is identical in both directions).
- Passenger path constraints are restrictions on passenger movement and are: '*maximum number of transfers per path*' (mainly for computational reasons) and '*infrastructural & geographical pricing level*' (excluding unprofitable passengers)

3.2 Solution strategy

Best fitting the problem is a Line Generation & Configuration (LGC) strategy (Figure 1). This consists of five main components: from input '*Input*' (problem definition) via three main procedures: the '*Line Generation*' (builds pool of lines), '*Line Configuration*' (line selection), and '*Network Analysis*' (assessment of lines) to '*output*'. The steps are further elaborated in Figure 2.

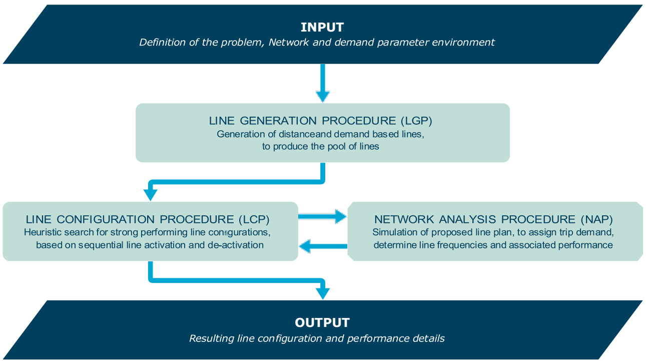

Figure 1: High-level Line Generation and Configuration approach

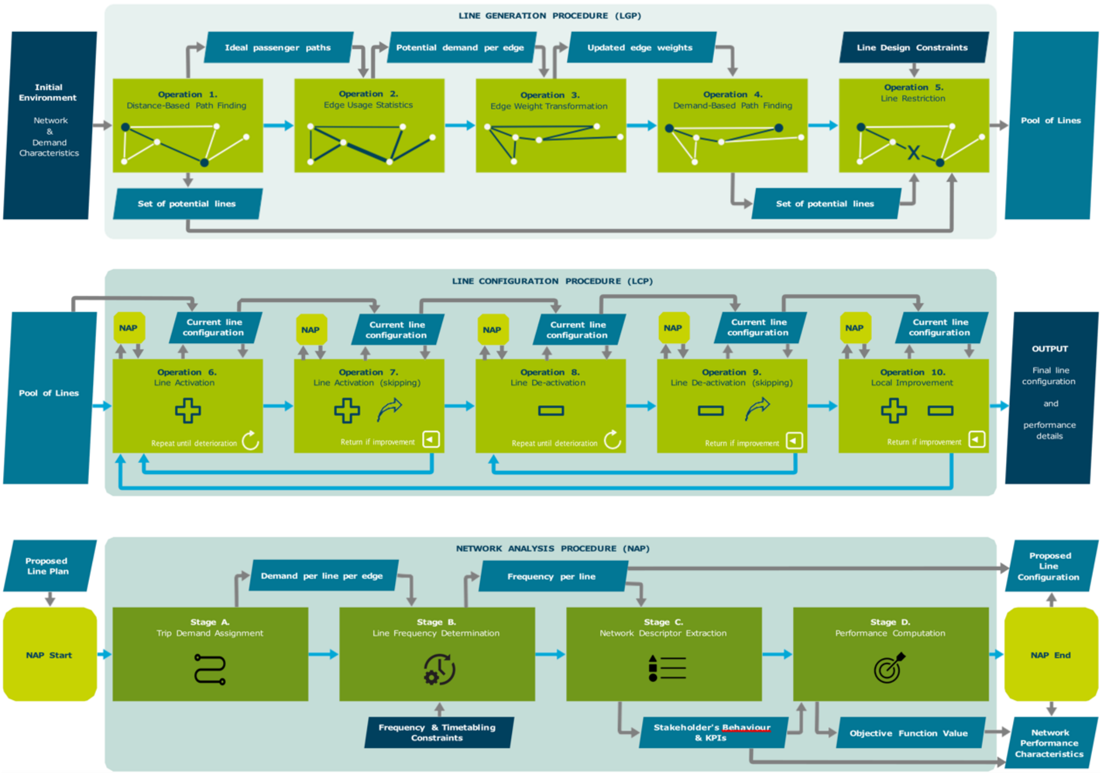

Figure 2: Flowcharts of Line Generation (top), Line Configuration (middle) and Network Analysis (bottom) procedures.

3.3 Case Study of the European Network

The characteristics of the European continent have been captured in the components of the input in search of the potential significance of a European high-speed rail network. The vertices in the graph are described using 124 cities and 385 airports. The former based Donners (2016), the latter by extracting the main airports from Eurostat (2020). The model distinguishes three modes of transport: air, road and high-speed rail. Rail and air networks are derived from the above mentioned sources. The road network is difficult in realistically capturing natural and political barriers (e.g. water bodies, mountains or country borders) by a mathematical function, car travel times and distances are estimated using the API of Heidelberg Institute for Geoinformation Technology (2020). Each mode is provided with time-components as access/egress, waiting time, transfer time and in-vehicle time based on repective speeds. The three objective functions for *'Users', 'Operators' and 'Society'* are filled with real world data. Value of time for the user are derived from Kouwenhoven et al. (2014), but correcting for inflation, wealth differences and uncertainties €50/h and differentiated for trip-stages (€67,5/h acces/egress and €75/h waiting and transfer). Operation is valued at €0,130/seat.km and maintenance at €0,0122/seat.km (Campos and de Rus, 2009). The negative impacts of transportation on its surroundings are expressed in the external costs. Following CE Delft (2019), seven main externalities for long-distance transport are considered: '*accidents*', '*air pollution*', '*climate*', '*noise*', '*congestion*', '*wellto-tank*' and '*habitat damage*'. The minimum line length was set on 200km, minimum number of stops at 3, operating window at 18 hours and minimum frequency at one giving the opportunity to daily trains as zon-Thalys.

Due to the complexity of accurately estimating the demand for long-distance transportation using socio-demographic characteristics, it was opted to use observed travel data of the airline industry in 2019, as collected by Eurostat (2020). Three main challenges needed to be overcome: (1), the observed flows only represent traffic between airport-pairs, rather than city-pairs. (2), the airports are frequently part of more complicated multi-airport-city systems, which makes that their traffic cannot be 1-on-1 assigned to a specific city. (3) air traffic only represents a portion of the total demand and that this portion varies per OD-pair, mainly depending on the level of services (travel time) compared to other modes.
The raw air traffic flows were transformed using a novel methodology that fits the expected travel behaviour between each city-city pair to the relevant airport-airport traffic flows. This was done by (1) determining the city-airport systems, (2) making an inventory of possible flight paths between city-city pairs, (3) estimating the possibility of each flight to be taken and (4) comparing the averaged flight with other modes to compare its competitiveness. Following this, (5) the observed airport-airport demand volume was assigned to city-city pairs based on the likeliness of their route and the competitiveness to other modes. Finally, this air demand between city-pairs was extrapolated using the findings of Donners (2016) on the expected market share for air traffic per distance unit.

The demand estimation resulted in a total number of 2.140.000 trips per day within the network, with demands ranging between a maximum of 20.600 and a minimum of 0,96 passengers/day/OD. Across the network, flows were observed for 5.174 out of 7.688 possible OD-pairs. Only the largest OD-pairs (90% of the network's demand), were considered. This resulted in ODs having less than approximately 40 passengers per day to be eliminated. This made that only 985 OD-pairs had to be evaluated.

3.4 Experimental set-up

The implementation of the model were written in '*Python 2.7.16*' using '*Spyder 3.3.6*'. All tests were performed using a PC with Intel® processor, Core™ i5-8500, 3.00GHz and 16GB RAM memory. Evaluation was on a smaller problem (Germany: 17 cities, 18 possible lines). The exhaustive search required 10.486 seconds, the heuristic managed to reach global optimum in 379 seconds. Simulation of the full European problem would take 70 years per simulation. Three measures were taken to reduce computation times, this resulted the heuristic search requiring 3-5 days to complete. Standard parameterised simulations were not able to develop into an integrated network, leaving multiple not-connected sub-networks. This is caused by disadvantageous passenger paths: those that make a detour to avoid (1) geographical barriers and those that make an (2) infrastructural detour (both in distance and time) from their shortest paths. Characteristic for these paths is that they provide the user with fewer benefits, whilst imposing higher operator costs, thus decreasing the cost/benefit ratio. Hence the infrastructural and geographical constraints.

The analyses are structured under 4 experiment with one or more scenario simulations:

- **Experiment 1:** Est. of the current network's characteristics and performance
- **Experiment 2:** Analysis on pricing and governance strategies *(Alterations on objective weights and governance related parameters)*
- **Experiment 3:** Analysis on high-speed rail design variables *(Alterations on vehicle, passenger path and line design variables)*
- **Experiment 4:** Assessment of synthesised scenarios.

4. Results

Results of the experiments 2, 3 and 4 are each discussed in a section. The results of experiment 1 as benchmark are presented here.

Experiment 1 is characterised by the current policies: the EU's believe in a competitive railway market (thus '*Free market*' governance structure) and a pricing environment where societal costs are not internalized. This scenario has been able to develop into a well functioning HSR system, (positive C/B-ratio of €24.9 million per day and its large AirRail substitution of 14.7 %, and reaching 89 cities. It still experienced difficulties in connecting sub-networks, which is confirmed by the low share of transfer passengers (only 7,5% with single transfer*)*. This first simulation should rather be seen as a lower boundary for later comparisons.

Table 1: Effects of pricing governance strategies

	1. Liberalisation	2. Total Welfare	3. Total Welfare	4. Mobility	5. Sustainability	6. Future Proof
ψ^{User}	50	33	33	50	25	38
$\psi^{Operator}$	50	33	33	25	25	25
$\psi^{Society}$	0	33	33	25	50	38
	Free market $C^{operator} - 20\%$		Centralised organisation $t^{transfer} - 50\%$			
Number of lines	96	100	100	123	130	143
Connected vertices	93	100	100	105	107	109
Reachable ODs	76	119	100	165	173	169
Centre focused	97	99	100	100	103	102
Total benefits	92	113	100	92	97	97
User Benefits	90	97	100	114	115	117
Operator costs	85	84	100	143	143	143
Societal Benefits	84	101	100	127	134	129
Available seat km	85	105	100	143	143	143
Avg. load factor	97	97	100	95	102	97
Avg. line length	105	108	100	109	99	106
Avg. no. stops / line	100	103	100	108	103	110
Avg. freq. / line	86	92	100	102	107	92
Modal split air	102	100	100	96	94	95
Modal split HSR	85	102	100	125	131	128
Modal split car	105	100	100	92	91	92
Avg. HSR trip dist.	97	101	100	108	110	108
Share direct pax	111	105	100	93	87	96
Share 1-trf pax	48	84	100	129	162	118
Share 2-trf pax	28	40	100	171	155	103
Revenue pax km	82	102	100	136	145	138

Explanation: Normalised development of KPIs for policy alterations, indexed (100) at '3. Total Welfare (CO)' scenario

4.1 Effects of pricing and governance strategies

To test the effect of different pricing policies and governance strategies, six diverging scenarios were simulated in '*Experiment 2*' (see **Fout! Verwijzingsbron niet gevonden.**). The two main governance structures are defined as the '*free market*' (sc. 1,2), which benefits from competition and subsequent cost-efficiencies, and the '*centralised organisation*', that benefits from better network integration with shorter transfer times. Different pricing scenarios were resembled by the adjustment of weights (ψ) in the objective function. These weights ranged from the non-consideration (sc. 1), actual internalisation (sc. 2,3) and active sub sidisation/taxation of societal costs (sc. 4,5,6). Given the unlikeliness of combinations, a selection was made.

Governance: Isolating the divergent characteristics of governance strategies, (sc. 2 & 3), indicates a stronger cost-efficiency of a free market (total benefits), whilst offering relatively similar extensiveness (RPK, #lines, connected cities) and performance (user & societal benefits), when compared to the centrally organised network. The benefits of the free market scenario mainly find their origin in the substantial reduction of operator costs.

Pricing: The internalisation of external costs induced a strong growth in the extensiveness (ASK, RPK, # transfer pax) and the performance of the network. However, mixed results are found for the ratio between costs and benefits. In free market, the inclusion of societal interests in the design considerations leads the development past a design barrier, hence allowing for a more extensive network. This extended network is then able to take advantage of a better integration KPIs (more transfer passengers, higher load factors), inducing a better cost-benefit ratio. The centralised scenarios, leads to lines that are not necessarily the most cost-efficient, but that do contribute to goals (sustainability, mobility or social cohesion). As a result C/B-ratio improves.

4.2 Importance of HSR Design Variables

An overview of the observed relations is displayed in Table 2. The studied parameters are stated on the vertical axis, the effect on KPIs, related to goals, on the horizontal. The values are the average expected of the KPI given the defined interval of the design variable. An exemption applies to values that reached peak value (optimum), indicated with an asterisk. Below, the vehicle, line and passenger path features are discussed.

Vehicle Characteristics: Increasing the cruising speed allows for a higher level of service and contributing to all policy goals. A higher seating capacity makes it harder for the operator to accurately assign capacity, resulting in a lower performance and a smaller network. Both effects can be expected to be tempered in more detailed design stages, as faster vehicles increase for example acquisition costs, whilst the inclusion of heterogeneous vehicles or economy of scale advantages might favour larger vehicles.

Line design: The lower rows of Table present the adjustments in the lines that compose '*Pool of Lines*'. The most important observation regards the usage detour. The inclusion of slightly demand-based lines is beneficial to most user and societal goals, although it also comes at the cost of operator efficiency. A performance peak exists when constraining the minimum number of stops to three per line.

Passenger path features: The necessity of passenger path control was demonstrated by the development of non-connected '*sub-islands*' in unrestricted simulations. The same section also provided a context to the findings of Table 2.

Table 2: Measured relations between HSR design variables and KPI contribution to policy goals

						Operator (cost-efficiency)				User (mobility)			User (soc. cohesion)			Society (sustainability)		
						Total costs savings	**Operator costs**	**Avg. load factor**	**Share transfer pax**	**User costs savings**	**APK HSR**	**Share direct pax**	**No. connect cities**	**Reachable ODs**	**No. of lines**	**Societal costs savings**	**RPK HSR**	**% HSR**
	Parameter	**Unit**	**Range**	**Interval**	**Base→ Peak⋆ ↓**	€ $2-2{,}5\cdot10^7$	€ $2-3{,}5\cdot10^7$	$60-65\%$	$10-20\%$	€ $3-4\cdot10^7$	$275-625\cdot10^6 km$	$80-90\%$	$90-115(of 124)$	$400-1150(of 1300)$	$50-90$	€ $1-1{,}5\cdot10^7$	$175-375\cdot10^6$ km	$15-30\%$
Vehicle	**Cruising speed**	$[km/h]$	225-375	50	*n/a*	1.276	1.145	1.002	1.213	1.238	1.145	0.946	*Var.*	1.070	1.021	1.090	1.148	1.102
Vehicle	**Seating Capacity**	$[seats]$	350-600	50	*n/a*	0.994	0.963	0.994	0.947	0.980	0.963	1.013	0.985	0.937	0.950	0.964	0.958	0.966
Passenger Path	**Max. no. of transfers**	$[trf.]$	0 - 2	1	⋆1	0.970⋆	1.087	0.945⋆	*Var.*	0.968⋆	1.087	*Var.*	0.990	1.233	0.939⋆	0.903⋆	0.887⋆	1.089⋆
Passenger Path	**Avg. transfer time**	$[min]$	15 - 60	15	⋆30	0.979	0.917	0.997	0.722	0.945	0.917	1.070	0.952⋆	0.915	1.017	0.931	0.913	0.934
Passenger Path	**Geo. detour excl.**	$[-]$	1.05-1.25	0.05	*n/a*	1.106	1.107	1.008	*Var.*	1.110	1.107	*Var.*	*Var.*	1.162	*Var.*	1.097	1.117	1.114
Passenger Path	**Infra. detour excl.**	$[-]$	1.05-1.25	0.05	*n/a*	0.974	1.030	1.003	1.066	*Var.*	1.030	0.983	*Var.*	1.059	1.016	1.022	1.033	1.022
Line Design	**Min. no. of stops**	$[stops]$	2 - 6	1	⋆3	0.924⋆	*Var.*	0.955⋆	0.886	0.962⋆	*Var.*	1.029	*Var.*	*Var.*	0.925⋆	0.976⋆	*Var.*	0.975⋆
Line Design	**Usage detour factor**	$[-]$	0 - 1	0.125	⋆0,125	0.987	0.977⋆	0.996	1.017	0.986⋆	0.964⋆	0.996	*Var.*	0.983	0.980	0.983⋆	0.980⋆	0.985⋆
Line Design	**Geo. detour constraint**	$[-]$	1.25-1.75	0.25	*n/a*	1.009	1.017	1.008	0.844	1.015	1.018	1.040	1.048	1.048	1.150	1.013	1.025	1.017
Line Design	**infra. detour constraint**	$[-]$	1.25-1.75	0.25	⋆1,50	0.984⋆	0.986⋆	1.001	0.977	0.985⋆	0.986⋆	1.006	0.976⋆	0.989⋆	1.050	0.985⋆	0.987⋆	0.988⋆

- Explanation: Base value is expected to change with the relation factor when increased by the interval of the parameter
- Special case - peak⋆: Base value reaches top at peak and changes with same relation⋆ factor in both directions
- Special case - var.: no clear pattern could be identified.

4.3 Potential impacts of improved design

'*Experiment 4*' uses the lessons from previous experiments to determine the typical design characteristics and potential impact of improved HSR line configurations. Two synthesised scenarios were defined and tested, with the following adjustments: First of all, both scenarios were limited the maximum transfer to 1 and releasing the geographical detour. Furthermore, it was chosen to set the geographical and infrastructural strategic pricing level to the tested values. The first scenario, '*Economical*', described a low-effort solution that aims for a high cost-efficiency, with a '*free market*' governance structure with an equal distribution of objective function weights for all stakeholders. Moreover. The second scenario, '*Extensive*', works from a '*centralised*' governance structure (-50 % transfer time), which is actively subsiding for user and societal benefits. Here, the pool of lines is supplemented with demand based-routes. These outcomes are a base for further analyses.

The simulations led to the observation of multiple recurring patterns in their network design. All scenarios resulted in functional highlevel networks with similar shapes, although deviating in more characteristic details. A visualisation of the resulting line configuration for the extensive scenario is presented in Figure 3, colours indicate individual services and the width associated frequencies. The map provides insights in the dimensions of the network, as well as in the focal points, which are comparable for each of scenarios. Most notable is that the majority of lines that are visiting multiple countries, which indicates the importance of interoperability and cross-border cooperation, as these are justified by the transport demand patterns. Furthermore, it can be seen that most connected cities serve a certain degree of transfer passengers, although the network also focuses its lines towards specific hubs, of which Munich is the strongest example. Below, the design aspects over the lines and the networks they make are further discussed.

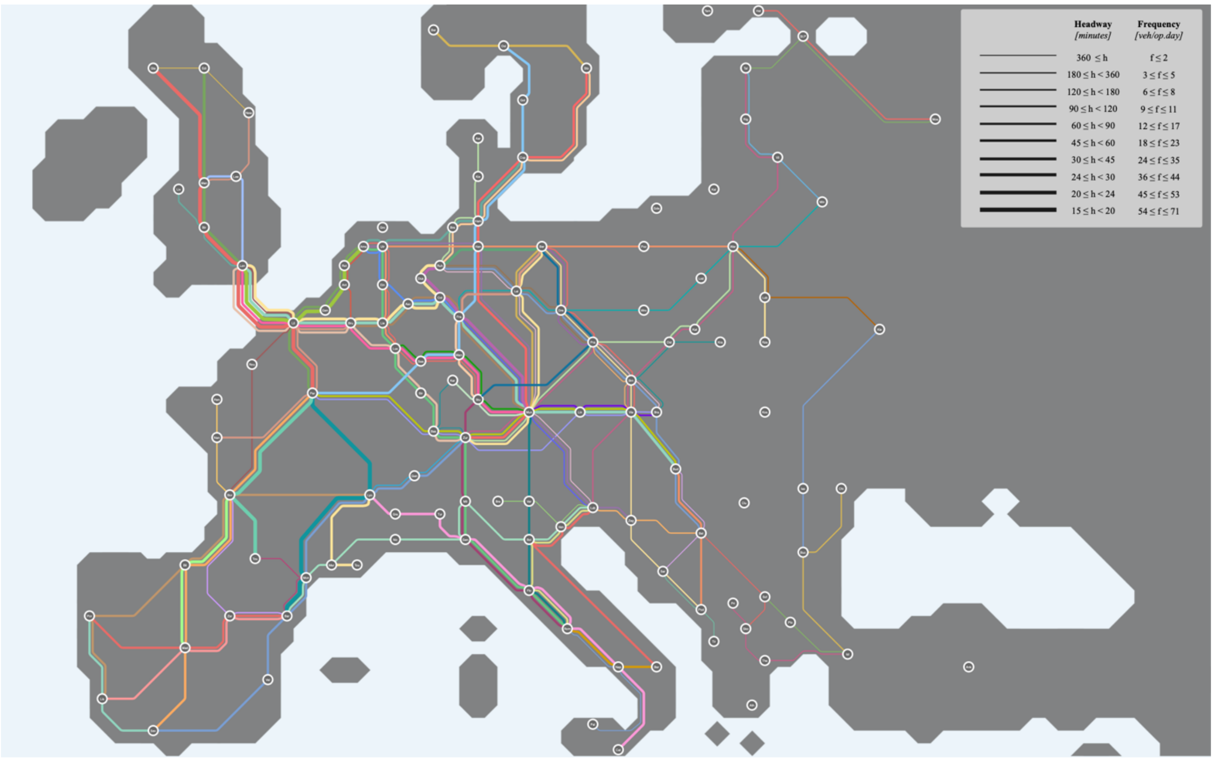

Figure 3: Transit map of the extensive HSR network

Network design: All simulations have a development of lines throughout the continent, but also show a similar decisions on the exclusion of cities or regions that do not justify connections because of their demand or geographical characteristics. Visually analysing the networks resulted in tree main aspects. (1), Network density increases towards the geographical centre of the map, in this case Germany. Especially Munich was consistently assigned with a hub function, followed by the other predominant German cities and more peripheral focal points like London, Lille, Bordeaux, Bologna, Copenhagen, Zurich, Warsaw, Budapest and Bucharest. This indicates that hubs are not only the largest cities, but also those strategically located. (2), Network extensiveness and density are slightly skewed to the west, given the lower demand in Eastern Europe. (3), Frequently unvisited cities are those with a lower demand which are not located between at least two higher demand cities (e.g. Rouen, Toulon, Groningen & Gdansk). This explains that these cities do not provide enough aggregated demand to justify a separate line.

Line design: Four recurring line types were distinguished: (1), all networks accommodate 5-20 (depending on the extensiveness) relatively long lines (length>1.000km; number of stops >6) that can frequently sustain hourly services (~18 veh/dir/day), the so-called '*main arteries*'. These lines are selected during the early phase of development and follow routes with relatively high and stable demands along the visited vertices, such that they benefit from so-called '*roof tile effects*'. Following, the majority of lines have a shorter profile (length <1.000km), which can be further subdivided into three categories. The second (2) type of line strategically connects to the main arteries, such that new cities are linked to the network. A decision which is justified by the aggregated demand related to these newly introduced cities. The third (3) category concerns lines that produce enough demand by themselves, which means that they are found in both low and high-density areas. Finally, (4) additional lines, which primarily follow a one or a few legs of a main artery, to allow for the more specific assignment of seating capacity.

To find to what extend the improved scenarios can potentially contribute to the policy goals of mobility and sustainability, they are compared with each other and the Initial scenario of the first experiment.

Geographically dependent performance: Striking observations are (1) the increased edge loads towards geographical bottlenecks (Iberian Peninsula, Great Britain, Scandinavia); (2) the relatively high HSR market share for intermediate cities (Bordeaux, Edinburgh, Glasgow, Bari and Lyon), which can be explained by the more locally-oriented demand patterns whilst being large enough to attract multiple lines; and (3) the smallest vertices, which have flows that are considerably smaller than the capacity of one train (Lublin, Tirana, Pristina). The fact that these smaller cities are being connected can be partially explained by roof tile effects in line occupation.

Variations of network extensiveness: The descriptive KPIs, show unambiguous results for network development along the scenarios. This is primarily confirmed by the increased revenue passengers kilometres (RPK; +26%) and available seat kilome- tres (ASK; +27%) comparing the '*Economical*' to '*Extensive*' strategies; effects that are even bigger when comparing '*Initial*' to '*Extensive*' scenarios, (+125% RPK and +129% ASK).

Differences in induced modal shifts: The simulations showed an HSR trip substitution potential of 14.7% ('*Initial*'), 25.0% ('*Economical*') and 29.9% ('*Extensive*') respectively. The market share per distance is plotted in Figure 4. A comparison of the '*Economical*' and '*Extensive*' scenario shows that the latter is relatively strong on longer distances (600-1000 km), thus more competitive with air travel. This behaviour can be explained by the better network integration and coverage which allows for ease of travel.

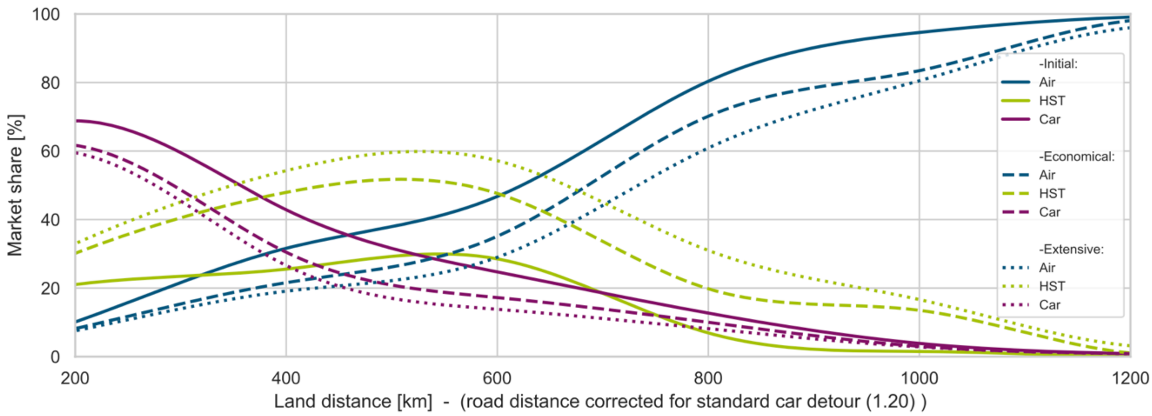

Figure 4: Modal Split per distance

Cost aspects and stakeholder benefits: From the user's perspective, benefits are primarily found for time savings in waiting (fewer air travel) and in-vehicle (fewer road travel) duration. Both factors strongly outweigh the newly introduced transfer times and increased access/egress times. This balance is again shifted towards longer HSR trips. For the societal (external) costs, the most substantial benefits of substitution towards HSR are found within the fields of accidents, congestion and climate. A reduction of external costs that was mainly induced by substitution from car traffic (72 %) as opposed to air traffic (28 %). Results show further that for a developed HSR network, only 31 % of societal benefits can be explained by environmental factors of air pollution, climate, habitat damage, noise. It leads to the conclusion that HSR can have even wider impact on society. Finally, the benefits of user and societal interests come at the expenses of the operator, who is usually able to pass these costs through by the pricing of tickets. Aiming for policy goals (mobility, social cohesion or sustainability) rather then cost-efficiency, the '*Extensive*' scenario provides a less-beneficial cost-benefit ratio to the '*Economical*'.

5. Conclusion

This study formulated a customised version of and solution strategy for the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in a long-distance transport environment for high-speed rail. This, to find the extent that the user, operator and societal performance of a European high-speed rail network be improved by centrally designed line configurations as well as pricing policies, and to find out such a network would look like.

This study found that the internalisation of external costs results in an improvement of the network performance and policy goals of enhanced mobility, social cohesion and sustainability. Performing this in a free market governance structure results in the best cost-benefit ratio, which is in line with the EU's believe in a competitive railway market. However, centrally designing and organising the HSR network in combination with actively subsidising and taxing for the user and societal interests significantly increases the network performances and contribution to the previously stated policy goals. This latter decision comes with a reduced cost-benefit ratio thus requiring governmental investments but also allowed for a growth of user and societal benefits approximating 1.8 times this investment.

Regarding the features of lines, it was seen that typical improved network designs comprise a certain number of longer (1000km-2000km) and high frequency (>18 veh/h) lines, so called '*main arteries*', often connecting multiple countries. These lines illustrate the importance of cross-border cooperation and rail interoperability. Furthermore, it was seen that not all cities nor countries were connected, as these are not justified from a network perspective. Both arguments plead for overarching design view, history has shown that the national and company interests resulted in a patchwork of poorly connected sub-networks. Strategic pricing (exclusion of unprofitable passengers) turned out to be indispensable for the development of a functioning HSR network. Such a pricing system requires a coordinated approach.

Concluding, the above arguments describe a situation which in contrast to the EU's believe in a free market and the current practice favour a centrally organised network and the internalisation of external costs, as substantial opportunities were identified for the policy goals of mobility and sustainability. However, these advantages come with a governmental monetary investment, an increased effort for the interoperability of infrastructure and a decreased sovereignty of member states with the willingness to subordinate national interests. The findings shed a new light on the current practice and provide political discussion with additional arguments on how to design the most successful European HSR.

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