A Unified Design of the European High-Speed Rail Network

Impacts of Design, Pricing and Governance Strategies

Grolle, J.

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Abstract — High-speed rail (HSR) is frequently seen as a promising alternative for long-distance travel by air and road, given its environmental advantages whilst offering a competitive level of service. However, due to a lack of knowledge on the design of HSR specific line configurations and the prioritisation of national and railway company interests, no real European HSR network has been realised yet. Together, these lead to a sub-optimal performance from a user, operator and societal perspective.

This research is the first attempt to apply the more frequently used '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) in an HSR setting, which searches the ideal set of lines and associated frequencies in a given network. To do so, this study developed a novel HSR generic model and solution algorithm, which were then parameterised for the European case. By benchmarking the current situation; analysing the relative importance of vehicle, passenger path and line design variables; evaluating pricing and governance strategies; and finally proposing improved settings; it was possible to assess impacts of improved design. The experiments showed that benefits for all stakeholders could be simultaneously enhanced when implementing a centralised governance and internalisation of external costs. This allowed the HSR market share to evolve from 14.7 % to 29.9 %, whilst also improving the societal cost-benefit ratio by 20.0 %. The governmental investment which is required to fill the gap from the most economical to the most extensive solution equals € 2.2 billion per year, but also provides a positive rate of return of 1.8 for the combined user and societal benefits. Additionally, the model demonstrated the necessity of spilling unprofitable passengers and the importance of improved cooperation. These followed from the strong network integration with overlapping and border crossing lines of substantial lengths, the contradiction between national and international interests and the high number of critical infrastructural elements.

All in all, this study demonstrated the possibility of using the TNDFSP in an HSR setting, which opens ways for further understanding of HSR network design. For this specific research, it allowed the identification of substantial opportunities for mobility and sustainability. These can be reached by improved design choices, internalisation of external costs and by relaxation of the desires for a competitive railway market and national sovereignty; all newly underpinned arguments for the discussion on how to design a successful (European) HSR system. Future research could greatly contribute by incorporating the construction of infrastructure, including timetabling or operational aspects, assessing different case studies in size and geography or introducing new technologies.

Keywords — High-Speed Rail , Europe , Network Design , Line Configurations , TNDFSP , Pricing , Governance

Full report — An electronic version of the full report is available at: https://repository.tudelft.nl/

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 (Janić, 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 (Givoni, 2006; Albalate and Bel, 2012; Pagliara et al., 2012; Donners and Heufke Kantelaar, 2019). 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. (Vickerman, 1996; Laperrouza and Finger, 2009). 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*.

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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 an HSR environment and the challenges to be expected.

2.1. Transit Network Optimisation Fields

Ideally, all aspects of a transit network would be designed simultaneously (Gallo et al., 2011). However, due to the highly complex working environment and stakeholder interests, the problem is frequently divided into smaller sub-problems (Desaulniers and Hickman, 2007; Ibarra-Rojas et al., 2015). A commonly used division considers six subsequent phases: (1) '*Network Planning*', (2) '*Line Planning*', (3) '*Timetable Generation*', (4) '*Vehicle Schedules*', (5) '*Crew Schedules*' and (6) '*Real-Time Management*' (Bussieck, 1998; Lindner, 2000; Lusby et al., 2011). The problems that quantitatively describe these phases can be encompassed under the name '*Transit Network Planning Problem*' (TNPP), as defined (Ibarra-Rojas et al., 2015). Because of cross-level relations between the sub-problems of the TNPP, works in this field often favou to combine several subproblems into one. Guihaire and Hao (2008) defined a framework of these combined problems. Pairing this framework the topic of this specific study on centrally designed HSR line configurations, it is established that the problem of this research can be classified in the category of '*Transit Network Design and Frequency Setting Problems*' (TNDFSP).

2.2. Transit Network Design and Frequency Setting Problem for HSR

The TNDFSP combines a (1) '*Design Problem*' (which determines a 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*' (the set of chosen lines) and their associated '*Frequencies*'. Together, they form the '*Line Configuration*' (Kepaptsoglou and Karlaftis, 2009; Schöbel, 2012). In search of previous literature, no studies applying this problem in an HSR environment 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: The objective function is the mathematical expression that reflects a goal which can either be minimised or maximised (Hillier and Lieberman, 2015). 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 (e.g. acquisition, operational and maintenance) and the user desiring a maximisation of its benefits (e.g. travel time, costs) (López-Ramos, 2014; Owais et al., 2016). Frequently, studies expand these stakeholder interests by incorporating a broader set of goals, such as the minimisation of external costs, transfer traffic, travel time and fuel consumption, or the maximisation of capacity or total (societal) welfare.

TNPP studies in the field of HSR show similar objective types: Yue et al. (2016) consider the maximisation of profit for a given fleet, Sun et al. (2014) try to minimise the travel times for trains, Gallo et al. (2011) separate car from transit users and Li et al. (2013) introduce a green perspective by incorporating the minimisation of energy use and carbon emissions. The analysis shows that most differences are not necessarily found in the types of objective functions, but rather the specification of the parameters, given their deviant characteristics when compared to conventional transit.

Decision Variables: Decision variables are the representations of quantifiable decisions to be made (Hillier and Lieberman, 2015). 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).

From the perspective of HSR, many resemblances with other transit modes can be found. This, because the mentioned decision variables are all focused on the high-level network and passenger flows, rather than operational factors. It makes that the decision variables do not require further expansion for this study.

Network Characteristics: A standard TNDFSP network consist of '*vertices*' (stops or stations), '*edges*' (direct connection between vertices), '*lines*' (passenger services residing a sequence of connected edges) and '*paths*' (passenger courses between two vertices following one or more lines) (Schöbel, 2012). In general, these networks come in three typical structure types: '*simplified radial structures*', '*simplified rectangular grid structures*' and '*realistic irregular grid*' structures (Kepaptsoglou and Karlaftis, 2009). Furthermore, a distinction can be made in the modes available (uni- or multi-modal) as well as the ability for traffic to interact with vehicles of the same or other modes. (Farahani et al., 2013).

Regarding other network optimisation research in the field of HSR, it is seen that most studies (e.g. Allard and Moura (2014) and 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. However, 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 by Kepaptsoglou and Karlaftis (2009): a '*one-to-many*' demand pattern (used when 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. Zhao and Zeng (2007) and Hassan et al. (2019). Secondly (2), the '*time scope*' varies between years for highly discrete problems concerning the construction of infrastructure and minutes for tactical and operational problems (Farahani et al., 2013; Ibarra-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, e.g. Cervero (2002), Laird et al. (2005), Di Giacinto et al. (2012) and Beaudoin and Lin Lawell (2018)) and '*fixed or elastic mode specific demand*' (when evaluating mode substitution, e.g. Janić (1996))

For a TNDFSP in the HSR domain on the European continent, it is considered that '*many-to-many*' demand pattern and a relatively longer '*time-scope*' are required. Furthermore, considering '*elastic demand patterns*' could strongly increase the accuracy. However, the most characteristic difference in the demand for an HSR problem is not mentioned above. Many of TNDFSPs for conventional transit systems assume demand to be generated by residential zones (e.g. Fan and Machemehl (2008) and Heyken Soares et al. (2019)). For long-distance transport, however, the generation of demand must be sought in other factors. The implementation of this will be discussed more elaborately in *section 3.3*

Constraints: Imposing constraints on any optimisation problem ensures realistic solutions, but it also contributes to the reduction of computational requirements (Bussieck, 1998). In a search for unification of fundamental line planning models, Schöbel (2012) identified constraints which mainly concern budget, capacity and connectivity requirements. Including more practical works, 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 the importance of line design constraints, such as directness, length, shape, and load factor requirements.

Characteristic of rail transport is the relative dependence on its infrastructure and the subsequent requirements (Bussieck, 1998). In this category, especially constraints for operational factors (physical interoperability and safety systems, more complex station or edge capacities and difficulties in overtaking) and political factors (divergent governance or international political conflicts) play an important role (Ahuja et al., 2005; Yue et al., 2016). However, their complicated nature makes that they cannot always be quantified (Bussieck, 1998). Given the strategic character of this research, it means that the emphasis should be laid upon line design or potentially political constraints, rather than operational.

2.3. Solution Strategies

TNDFSPs are seen as relatively complex problems. In Baaj (1990) and Fan and Machemehl (2004), six main factors of complexity were identified: (1) the expression of decision variables and objective functions, (2) frequently occurring non-convex and non-linear costs, (3) NP-hardness due to a discrete nature bringing combinatorial complexity, (4) conflicting stakeholder objectives, (5) designing operationally feasible lines that obey design criteria and (6) the nature of variable transit demand. Combining this with the observation of (Schöbel, 2012), 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 (where a set of candidate lines is generated, after which a sub-selection of these lines are selected for the final network) and the '*Line Construction & Improvement*' method (which starts with an initial line plan that is step-wise improved by altering lines). The processes to guide and solve these problems follow one of two main techniques: either '*conventional techniques*' (analytical and mathematical programming) or '*heuristic techniques*' (heuristics and meta-heuristics) (Kepaptsoglou and Karlaftis, 2009; Iliopoulou et al., 2019). However, the application of conventional techniques is generally considered less suitable. For the analytical options, this follows from the problem being NP-hard and the results being opaque. For the mathematical programming, this follows from the inability of realistically representing the structure of lines (Ceder, 2001; Youssef et al., 2001; Fan and Machemehl, 2004; 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 (Sonntag, 1977; Quak, 2003). 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.

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3. METHODOLOGY

The main goal of this research is to assess to potential improvement that can be made in the design of HSR networks and to learn on the characteristics of such improved networks, as was formulated in the '*Introduction*' (*section 1*). Given the size, complexity and limited qualitative knowledge in the topic of HSR network design, it was chosen to use a quantitative approach. In *section 2*, it was found that a problem like this is numerically described by the '*Transit Network Frequency and Design Setting Problem*' (TNDFSP), which is more frequently used for conventional public transport systems. However, to make this applicable for this study, a range of adaptions had to be made. This chapter covers the methodological elaboration of this adapted problem, which is built upon a three-step approach: a generic '*problem formulation*', a generic '*solution strategy*' and a case-specific '*parameterisation*'. Additionally, the model is implemented to make it usable. An overview of this overall approach is presented below.

Methodological approach and chapter structure: The first step (1) (*subsection 3.1*) was to define a customised version of the TNDFSP, such that this quantitatively describes the problem of optimising HSR line configurations in a generic setting. The inherent complexity of these TNDFSP problems (as discussed in *section 2.3*), makes that these cannot be solved using conventional techniques. Because of this, the second step (2) (*section 3.2*) was to formulate a novel heuristic that strategically searches the solution space for strong performing results in a reasonable time. The final development step (3) (*section 3.3*), was to parameterise the newly described problem for the European case study, such that the simulation takes place in a realistic situation. By implementing the previously described model and constructing multiple experiments, as stated in *section 3.4*, it became possible to simulate multiple scenarios. Interpreting the outcomes of these different simulations allowed to ultimately assess the potential network improvement design characteristics of a unified HSR design.

Modelling choices: Several modelling choices were made to match the strategic character of the research, simplify the problem and emphasis the research goal. The study considers a continuous state perspective, such that the expenses for the construction of infrastructure or the acquisition of vehicles are not considered. The associated time-span of this continuous state equals one operational day of eighteen hours. In this state, all costs components are considered relative to a situation with no HSR whatsoever. Additionally, the network's infrastructure is uncapacitated to provide the problem with solution freedom. Below, an overview of further modelling assumptions is stated:

- The total demand is fixed (thus no generation effects)
- The mode-specific demand is elastic, based on the 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
- Vehicles do not interact whatsoever
- No operational strategies (e.g. deadheading or short-turning) are considered
- HSR infrastructure is interoperable throughout the network and not capacity or operationally restrictive
- 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*' $G = (V, E)$, which is composed of a finite set of cities that are represented as '*vertices*' $V = \{v_1, v_2, ..., v_{|v|}\}$ and a finite set of connections between these cities that are represented as '*edges*' $E = \{e_1, e_2, ..., e_{|E|}\}$. Furthermore, different ways of transport are distinguished by '*modes*' $M = \{m_1, m_2, ..., m_{|q|}\}$. Following this given graph, a '*line*' can be defined as a service that is a sequence of directly connected vertices: $l = \{v_{first}, ..., v_{last}\}$. Combining multiple of these separate line together results in a '*set of lines*' $L = \{l_1, l_2, ..., l_{|L|}\}$. Passengers travelling through this network using a single line follow a '*direct path*' p^d and passengers requiring a transfer to make their trip follow a so-called '*transfer path*' p^t. Together, these paths form the set of paths $P = \{p_1, p_2, ..., p_{|P|}\}$, where each pair of vertices has only one such path. An overview of sets and indices is presented in *Table 1*

TABLE 1: OVERVIEW OF SETS AND INDICES

Notation	Description
$i, j \in V$	Vertices (cities & stations)
$c \in E$	Edges
$k \in L$	Lines
$q \in M$	Modes
$p^d \subset P$	Direct path
$p^t \subset P$	Transfer path

3.1.1. *Parameters*

The succeeding steps of the problem definition use a range of parameters and variables to describe different components within the model. An overview of this is displayed in *Table 2*.

3.1.2. *Decision Variables*

The typical TNDFSP knows two main decision variables, which are also used for this study: the '*set of lines*' $L = \{l_{k=1}, l_{k=2}, ..., l_{k=L}\}$, where it is defined which selection of lines are to be activated, and the associated '*frequencies*'

TABLE 2: OVERVIEW OF PARAMETERS AND VARIABLES

Notation	Unit	Description
V	[-]	number of vertices v
$t^{acs}_{v,m}$	$[min]$	access time of vertex v for mode m
$t^{egs}_{v,m}$	$[min]$	egress time of vertex v for mode m
E	[-]	number of edges e
$ds^{gc}_{i,j}$	$[m]$	greater circle distance between vertices v_i and v_j
$ds^{land}_{i,j}$	$[m]$	land distance between vertices v_i and v_j (road distance corrected by standard car detour factor)
$ln^{str}_{e,m}$	$[m]$	stretching length of edge e for mode m
fc^{dt}_m	[-]	detour factor of transport mode m
$t^{rid}_{e,m}$	$[s]$	total riding time at edge e for mode m (incl. dwell time HSR; incl. taxi and take-off/landing air)
$ln^{str}_{l_k}$	$[m]$	stretching length of line l_k
$ln^{l_k,min}$	$[m]$	minimum line length for any route
cp_m	[-]	vehicle capacity of mode m
t^{trf}_m	$[min]$	transfer time for mode m
fc^{loa}_m	[-]	design load factor of mode m
$t^{l_k}_{i,j}$	$[s]$	total travel time between vertices i and j on line l_k
$t^{t_r}_{i,j}$	$[s]$	total travel time between vertices i and j along transfer path pt_s
$t^{rt}_{l_k}$	$[s]$	round trip time of line l_m (incl. buffer time)
$n^{veh}_{l_k}$	[-]	number of operating vehicles of mode m required on line l_k
$dm^{tot}_{i,j}$	$[pax/day]$	Total travel demand between vertices i and j
$dm^{m}_{i,j}$	$[pax/day]$	travel demand between vertices i and j for mode m
$dm^{l_k}_{e_c(a,b)}$	$[pax/day]$	travel demand between vertices i and j on line l_k ;
$dm^{pd_r}_{i,j}$	$[pax/day]$	travel demand between vertices i and j along direct path pd_r
$dm^{pt_s}_{i,j}$	$[pax/day]$	travel demand between vertices i and j along transfer path pt_s
$q^{v,m}$	$[pax/day]$	number of passengers using vertex v with mode m
$q^{e,m}$	$[pax/day]$	number of passengers using vertex e with mode m
$q^{max}_{l_k}$	$[pax/day]$	maximum number of passengers using on the line l_k

$F = \{f_{l_{k=1}}, f_{l_{k=2}}, \ldots, f_{l_{k=L}}\}$ for each of the activated lines. An overview of this is given in *Table 3*. It should be noted that indirectly, the decision for these two variables also represents other design variables, as each lines comes with its own characteristics (Fan and Machemehl, 2008).

TABLE 3: OVERVIEW OF DECISION VARIABLES

Notation	Unit	Description
$L = \{l_{k=1}, l_{k=2}, \ldots, l_{k=L}\}$	[-]	set of lines
$F = \{f_{l_{k=1}}, f_{l_{k=2}}, \ldots, f_{l_{k=L}}\}$	[veh/d]	frequency on line l

3.1.3. *Objectives and costs components*

Based on the analysis of *section 2.2* and the character of the HSR environment, it is chosen to define the objective as the minimisation of the weighted (ψ) costs (C) as experienced by three main stakeholders: '*Users*', '*Operator*' and '*Society*'. Here, the weights are introduced to reflect the pricing policy trade-offs. The comprehensive objective function is presented in *Equation 1*. The separate stakeholder costs components are further expanded in *Equation 2* (user), *Equation 3* (operator) and *Equation 4* (society).

$$Min.\;\; Z = (\psi^{user} \cdot C^{user}) + (\psi^{ope.} \cdot C^{ope.}) + (\psi^{ext.} \cdot C^{ext}) \tag{1}$$

where:

Z = Objective function value
ψ_x = weight for stakeholder x
C_x = Total costs for stakeholder x

User costs The user costs follow from the time spent on travelling and the associated monetary value that is given to this time (Value of Time, indicated as *VoT*). With this, it follows that the user's objective is to minimise its travel costs. Dependent on the mode, a trip can consist of five elements: the (1) '*access time*', (2) '*waiting time*', (3) '*in-vehicle time*', (4) '*transfer time*' and (5) '*egress time*'. The overall user costs are determined by summing number of passengers q that spend a time t at a specific point. The formula describing the user costs is given in *Equation 2*.

$$C^{user} = c^{access} + c^{waiting} + c^{in-vehicle} + c^{transfer} + c^{egress} \tag{2}$$

where:

$$\begin{aligned}
c^{access} &= VoT^{acs}\left(\textstyle\sum_m \sum_v \left(q^{acs}_{v,m} + t^{acs}_{v,m}\right)\right)\\
c^{waiting} &= VoT^{wai}\left(\textstyle\sum_m \sum_v \left(q^{wai}_{v,m} + t^{wai}_{v,m}\right)\right)\\
c^{invehicle} &= VoT^{inv}\left(\textstyle\sum_m \sum_e \left(\left(\sum_{p_d}\left(q^{e,m}_{p_d,e}\right) + \sum_{p_t}\left(q^{e,m}_{p_t,e}\right)\right) \cdot t^{inv}_{e,m}\right)\right)\\
c^{transfer} &= VoT^{trf}\left(\textstyle\sum_m \sum_{p_t}\left(\sum_{i,j} q_{m,p_t} \cdot \left(n^{trf}_{p_t} \cdot t^{trf}_m\right)\right)\right)\\
c^{egress} &= VoT^{egr}\left(\textstyle\sum_m \sum_v \left(q^{egr}_{v,m} + t^{egr}_{v,m}\right)\right)
\end{aligned}$$

Operator costs The operator is responsible for running the HSR network, which means it has an interest in minimising these costs. The main costs components for operating a high-speed rail system, as defined by Campos and de Rus (2009) and Zschoche et al. (2012), are covered in the (1) '*operational*' and (2) '*maintenance*' expenses, which are expressed in cost per seat-kilometre. The numerical formulation of the operator cost components are further defined in *Equation 3*.

$$C^{operator} = c^{operational} + c^{maintenance} \tag{3}$$

where:

$$\begin{aligned}
c^{operational} &= \textstyle\sum_{l_k \in L}\left(2 \cdot ln^{str}_{l_k} \cdot f_{l_k} \cdot cp_{hsr}\right) \cdot c^{oper.,marg}\\
c^{maintenance} &= \textstyle\sum_{l_k \in L}\left(2 \cdot ln^{str}_{l_k} \cdot f_{l_k} \cdot cp_{hsr}\right) \cdot c^{main.,marg}
\end{aligned}$$

Societal costs The societal costs follow from indirect effects that are not paid by the actual user or operator, but rather by society. Internalising these so-called '*external*' costs is done by *Equation 4*, where the flow of passengers is combined with the mode-specific overall external costs per passenger-kilometre.

$$C^{society} = c^{external} \tag{4}$$

where:

$$c^{external} = \textstyle\sum_m \sum_e \left(\left(\sum_{p_d}\left(q^{e,m}_{p_d,e}\right) + \sum_{p_t}\left(q^{e,m}_{p_t,e}\right)\right) \cdot ln^{str}_e \cdot c^{ext,marg}_m\right)$$

3.1.4. Constraints

The objective function of *Equation 1* is subject to a range of constraints. This, to ensure feasible results and to restrict the solution space thus associated computational burden of the problem. The constraints are divided into three categories: '*Line Design constraints*', '*Line Frequency constraints*' and '*Passenger path constraints*'.

Line design constraints: The formulas below present the line design constraints. The constraints concerning the '*minimum line length*' (*Equation 5*) and '*minimum number of stops*' (*Equation 6*) prevent nesting with conventional rail and assure a network function. Following, the '*round trip time*' (*Equation 7*) imposes that all trains should be able to return to their home station within one operational day, to keep balance and allow for practicalities like maintenance. Next, the '*line symmetry*' (*Equation 8*) says that all lines should be identical both directions and finally, *Equation 9* and *Equation 10* prevent the inclusion of strongly detouring lines, mainly to reduce the computation time.

Minimum Line Length:

$$ln_{l_k}^{str,min} \leq ln_{l_k}^{str} \qquad \forall \qquad l_k \in L \tag{5}$$

Minimum Number of Stops:

$$n^{s_l,min} \leq n^{s_l} \qquad \forall \qquad l_k \in L \tag{6}$$

Round Trip Time:

$$t_{l_k}^{rt} \leq t_{l_k}^{rt,max} \qquad \forall \qquad l_k \in L \tag{7}$$

Line Symmetry:

$$l_k(i,j) = (\ l_k(j,i)\ )^{-1} \qquad \forall \qquad i,j \in V \tag{8}$$

Infrastructural detour (time & distance):

$$ln_{l_{k(i,j)}}^{str} \leq fac^{dt,infra} \cdot p_{i,j}^{d,min} \tag{9}$$

Geographical detour:

$$ln_{l_{k(i,j)}}^{str} \leq fac^{dt,geo} \cdot ds_{i,j}^{gc} \tag{10}$$

Frequency constraints: Below, the frequency constraints are presented. Given the strategic character of this study, they are mainly responsible for safeguarding feasible solutions, rather than user and operator friendly timetables. The '*minimum frequency*' (*Equation 11*) ensures non-negativity and prevents ghost lines, which are active but have no trains. The '*integer frequency*' (*Equation 12*) restricts the model from using partial trains. Finally, the '*frequency symmetry*' (*Equation 13*) guarantees the continuity of trains by making sure the frequency is identical in both directions of a line.

Minimum Frequency:

$$f_{min} \leq f_{l_k} \qquad \forall \qquad l_k \in L \tag{11}$$

Integer Frequencies

$$f_{l_k} = \mathbb{Z} \qquad \forall \qquad l_k \in L \tag{12}$$

Frequency Symmetry

$$f_{l_k(i,j)} = \left(f_{l_k(j,i)} \right)^{-1} \qquad \forall \qquad i,j \in V \tag{13}$$

Passengers path constraints: The passenger's ability to travel through the network is bounded by the constraints as presented below. Firstly, *Equation 14* limits the maximum number of transfers per path. This constraint is mainly for computational reasons, but it is also an essential tool for the design and performance of the network, as will be found in *section 3.4.2* and *section 4.3*. Similarly, *section 3.4.2* proves the necessity of excluding unprofitable passengers from the system, which is quantitatively described by the strategic pricing levels of *Equation 15* and *Equation 16*.

Maximum number of transfers:

$$n_{p^t}^{trf} \leq n_{p^t}^{trf,max} \qquad \forall \qquad p^t \in P \tag{14}$$

Infrastructural Strategic Pricing Level:

$$p(i,j) = \begin{cases} feasible, & \text{if } t_{p(i,j)}^{inv\&trf} \leq fac^{SPL,infra} \cdot t_{p^d(i,j)}^{inv,min} \\ infeasible, & \text{otherwise} \end{cases} \tag{15}$$

Geographical Strategic Pricing Level:

$$p(i,j) = \begin{cases} feasible, & \text{if } ln_{p(i,j)}^{str} \leq fac^{SPL,geo} \cdot ds_{i,j}^{gc} \\ infeasible, & \text{otherwise} \end{cases} \tag{16}$$

3.2. Solution Strategy

The fundamental solution strategies of Kepaptsoglou and Karlaftis (2009) (as discussed in *subsection 2.3*) require either a starting network of which the lines can be altered (Line Configuration & Improvement; LCI) or a set of lines from which a selection can be made (Line Generation & Configuration; LGC). Given the currently limited available knowledge on how such networks or lines should look like, it is chosen to use the latter option (LGC) and provide the system with a diverse palette of lines. In *subsection 2.3*, it was found that conventional solution strategies are non-sufficient for real-scale problems due to six characteristic difficulties of TNDFSP, which makes the problem reliant on (meta-)heuristics. In search of a suitable method, multiple techniques were considered. Aiming for a light-weight model (to perform multiple tests), which uses few starting assumptions (due to limited knowledge on line configurations) but also comes to reasonably optimal solutions, it was chosen to develop customised hill-climbing heuristic approach starting from a fully deactivated pool of lines. *subsection 3.2.1* briefly discusses the high-level structure of the '*line generation and configuration*' procedure, which is then followed by a further elaboration of its components.

3.2.1. Line Generation and Configuration

A visualisation of the high-level '*Line Generation and Configuration*' approach is presented in *Figure 1*. The figure consists of five main components. As '*Input*', it receives the definition of the initial problem definition as discussed in *section 3.1* and the parameters of *section 3.3*. Together, these make an environment to work in. Executing a range of procedures, it works towards the '*Output*'. This output consists of a resulting line configuration (thus set of lines and frequencies) with their associated performance details.

To reach this state, three main procedures are used. Firstly, the '*Line Generation Procedure*' (LGP) builds a pool of feasible and strategically designed lines. These lines are then transferred to the '*Line Configuration Procedure*' (LCP). This procedure guides the search towards a strong performing solution by strategically selecting multiple sets of lines. The proposed configurations are simulated and assessed on their performance in '*Network Analysis Procedure*' (NAP). Following this, the LCP decides which next move is most suitable, meaning that the latter two are in continuous consultation with each other.

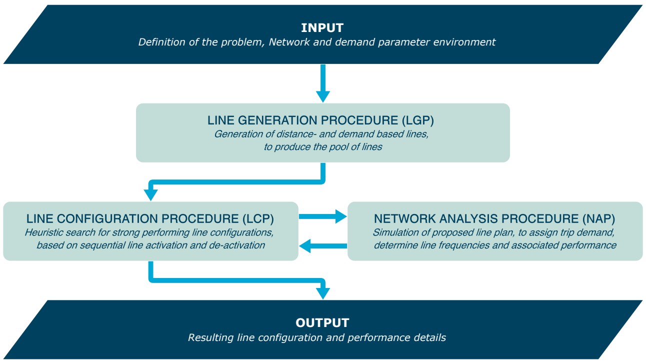

Fig. 1: High-level Line Generation and Configuration approach

3.2.2. *Line Generation Procedure*

Figure 2 provides an overview of the steps within the LGP. This procedure uses five operations to work towards the construction of two line types: Those based on shortest paths and those that are allowed to detour along edges with expected higher demands. Starting in '*Operation 1.*', Dijkstra's algorithm (based on travel times) is applied to find the shortest path between each OD-pair (Dijkstra, 1959). From this, all of the resulting paths are stored as potential lines.

Continuing, the demand-based lines are produced using the '*shortest-path-usage map*' technique, as defined by Kiliç and Gök (2014) and further developed by Heyken Soares et al. (2019). Here, the potential demand per edge follows from the assumption that all passengers would ideally follow their shortest path through the graph, which is done in '*Operation 2.*' by counting the expected traffic. Next, '*Operation 3.*' transforms the weights of the edges in the graph by combining the travel times and expected demand (by ratio $fac^{dt,dm}$), such that high-demand edges have relatively lower weights. In the succeeding '*Operation 4.*', Dijkstra's shortest-path algorithm is once again applied, but now with the new edge weights. This operation then presents the resulting demand-based paths to the set of potential lines.

Finally, the set of potential lines is reduced by enforcing the line design constraints of *subsection 3.1.4* in '*Operation 5.*' upon the set of potential lines, such that infeasible lines are excluded. This makes that the remaining lines constitute the '*Pool of Lines*'. However, the previous operations make that this pool could theoretically contain $2 \cdot \left(V^2/2\right)$ unique lines. The exponential character of this pool size makes that the problem becomes impracticable for larger networks, as will also be demonstrated in *section 3.4.1*. To further reduce the set of lines, two measures were taken: firstly, the designation of key-cities, which are the only vertices where lines can begin or terminate; and secondly the strategic elimination of lines, where a selection is made based on the closeness, highest demand destinations and highest expected line usage, to maintaining a diverse palette of lines.

3.2.3. *Line Configuration Procedure*

The Line configuration Procedure (LCP), as illustrated in *Figure 3*, is the heuristic that guides the search towards a strong performing solution by proposing possible line plans and comparing their performances. The LCP has a greedy hill-climbing character, and it consists of five operations. These operations are based on the activation, deactivation or substitution of the current line configuration.

The heuristic starts with an empty line plan. The first two steps ('*Operation 6.*' and '*Operation 7.*') are concerned with activating lines from the '*pool of lines*'. In every iteration, the solution space is defined as the individual activation of all currently non-activated lines, which bounds the number of iterations by the triangular number T_n, with n being the size of the '*Pool of Lines*'. Following this, the entire iteration solution space is presented to the NAP, where all moves are simulated separately. With its greedy character, the LCP selects the best performing move. '*Operation 6.*' then repeats this process until no further improvement is found. To reduce the risk of ending at a local optimum, '*Operation 7.*' repeats the same process, but with the ability to accept a maximum number of s temporary deteriorating iterations ($s = 10$ for this study). Finding a delayed improvement, the line configuration is updated and '*Operation 6.*' is restarted. If no further improvement is found, a continuation towards '*Operation 8.*' is made.

'*Operation 8.*' and '*Operation 9.*' are identical to the previous operations 6. and 7., although they work from the opposite perspective. Considering the current configuration, their solution space is defined as the deactivation of all currently active lines. Again, each best possible move is selected in Operation 8. and temporary skipping procedures are performed in Operation 9..

Finally, Operation 10. concerns the substitution of lines. Here the solution space is defined as the modification of all lines (active $\Longleftrightarrow$ non-active) and temporary deteriorations are accepted within an iteration. in the first sub-iteration, the n^{th} best move is selected ($n^{max} = 18$ for this study). In the following sub-iteration, three branches are constructed by selecting the 1^{st}, 2^{nd} and 3^{rd} performing moves. These branches were then deepened by performing a greedy search for three more levels. This sequence of sub-iterations is repeated for n^{max} times until an improvement is found. If this does not happen, the LCP is terminated.

3.2.4. *Network Analysis Procedure*

In *Figure 4*, an overview of the subsequent steps in the Network Analysis Procedure (NAP) is displayed. The NAP is responsible for the simulation of a proposed line plan, such that it can assess the performance of this line plan and inform the LCP on whether it is moving in the right direction. The above is done four separate stages.

The NAP starts on the left-hand side at '*Stage A*', where the user's behaviour is simulated by firstly (1) determining the best HSR path option and then (2) comparing this to the level of service of other modes. The HSR path determination is based on a lexicographic travel time and transfer minimisation strategy, as initially proposed by Han and Wilson (1982) and adapted by Fan and Machemehl (2004). This strategy is preferred over frequency share-based multipath assignments, due to the higher information transparency combined with long term trip planning, and flow-concentration techniques, due to the operator interest inclusion in other phases. Knowing the best HSR path, this stage continues its task by assigning the travel demand per mode. This assignment is based on travel time attributes by using the '*Random Regret Minimisation*' technique as developed by Chorus et al. (2008) and applied on long-distance transport by Donners (2016).

Consecutive to this, '*Stage B*' simulates the operator's response by determining the line frequencies that are required to supply for the demand per line, for which a design load factor of $fac^{lf}_{HSR} = 0{,}8$ was used. Furthermore, this is also the stage where the frequency constraints of *section 3.1.4* are activated to assure feasible solutions. It the following '*Stage C*', the network descriptors (such as average access/egress times or the number of required vehicles are extracted, such that model choices could be interpreted in post-analyses. Furthermore, the indicators are used to determine the performance (objective function value) in the last stage, '*Stage D*'. The resulting output is reverted to the LCP.

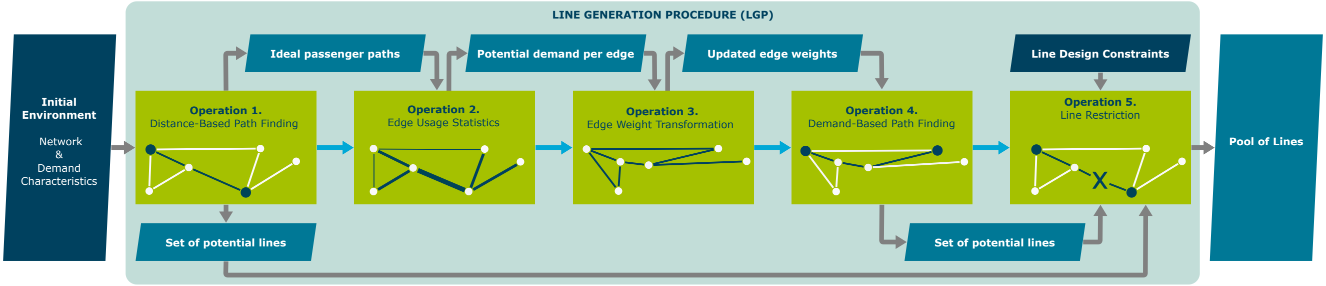

Fig. 2: Flowchart of Line Generation Procedure

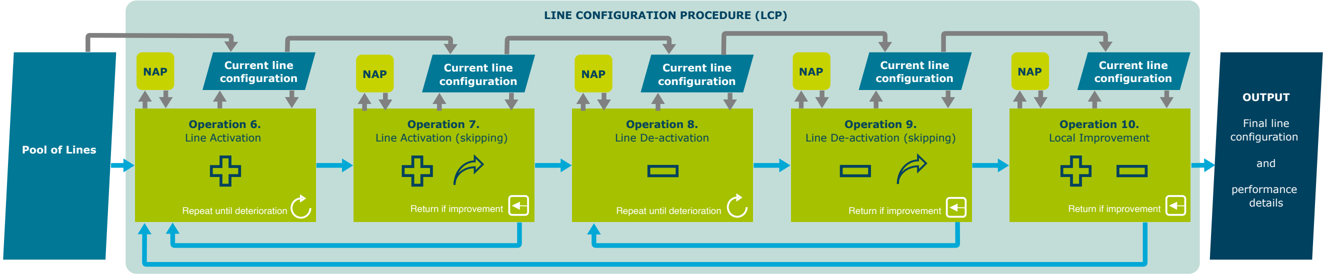

Fig. 3: Flowchart of Line Configuration Procedure

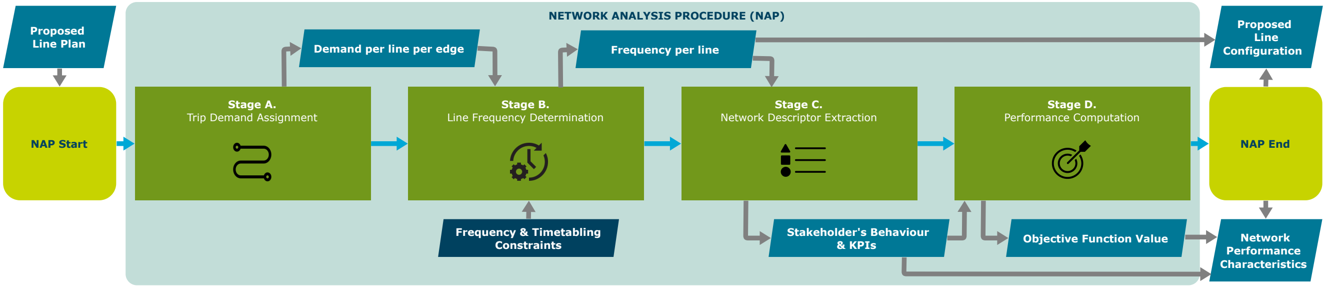

Fig. 4: Flowchart of Network Analysis Procedure

3.3. *Case Study of the European Network*

In search of the potential significance of a European high-speed rail network, the problem was parameterised to realistically describe the characteristics of this continent and currently available technologies. The paragraphs below discuss each of the main network components.

Vertices: The vertices in the graph are described using 124 cities and 385 airports. The former selection is based on the study of Donners (2016), in which the most significant metropolitan areas for a high-level European HSR network are defined using socio-demographic (e.g. population, GDP, research activities) and practical criteria (e.g. availability of rail infrastructure). The latter selection was found by extracting the main airports as reported by participant countries of the annual air-traffic questionnaire by Eurostat (2020). Estimations for access and egress times were location-specific. Within cities, to an HSR station, this time was the function of a city's area and the average time required to reach its centre, assuming an average travel speed of 30 km/h (Donners, 2016). From cities to airports, these average access and egress times were estimated by considering the passenger volume of and travel time to all airports within a 2.5 hours range.

Edges: The model distinguishes three modes of transport: air, road and high-speed rail. The edges in the air-network are again based on the questionnaire of Eurostat (2020), as this reports the actual flights between the modelled airports in 2019. Regarding the road network and considering the difficulty in realistically capturing natural and political barriers (e.g. water bodies, mountains or country borders) by a mathematical function, it was opted to estimate car travel times and distances using the application programming interface (API) of Heidelberg Institute for Geoinformation Technology (2020). This API searches for the fastest route for each OD-pair when considering the currently available road and ferry network. Finally, the high-speed rail infrastructure network is based on the Trans-European Rail network vision of European commission (2013) and the on this elaboration by Donners (2016). The central assumptions in this HSR network follow from the interoperability, the unconstrained capacity and the existence of infrastructure which is not always yet built. The length of each edge was found by converting the road distance, where a 0.91 detour factor is assumed for the HST when compared to the car (Donners, 2016).

Modes: Travelling between the vertices with one of the three modes results in different durations for the five main time elements of a trip, as introduced in *subsection 3.1.3*. The car has the most straightforward profile, as access/egress times, waiting times and transfer times are considered to be irrelevant. This makes that the in-vehicle time follows the actual travel time along the edge, which is supplemented with a rest factor of 10 %. Air travel times were composed of the city-specific access/egress times that differed per destination and a waiting time of 110 minutes (check-in, security, etc.). The in-vehicle times of this mode were estimated based on observed flights, which gave a cruising speed of 850 km/h and fixed take-off/landing and taxi procedures comprising 30 minutes and 50 km each. Finally, high-speed train trips are estimated by city-specific access/egress times, waiting times of 15 minutes and transfer times of 60 minutes (-50 % for a centralised organisation, as explained in *section 4.2*). Following this, the in-vehicle time per edge was composed using an average cruising speed of 275 km/h (Campos and de Rus, 2009), an acceleration constant of 0.3 m/s^2, a deceleration constant of 0.5 m/s^2 Connor (2014) and a dwell time of 5 minutes per stop. Furthermore, the trains are characterised by a capacity of 350 seats each (Campos and de Rus, 2009).

Stakeholders: The objective function represents the interests of three stakeholder groups: the '*user*', '*operator*' and '*society*'. The user's goal is to minimise its costs when travelling through the network. To translate these travel times to a monetary value, the value of time (VoT) is introduced. Following the VoT findings for long-distance transport in The Netherland of Kouwenhoven et al. (2014), but correcting for inflation, wealth differences and uncertainties, this value is estimated at 50 €/h. In addition, the VoT also varies along the stage of a trip. For this, the weights as found by Ramjerdi (2010) are applied. This brings VoT's of 50 €/h for the in-vehicle phase, 67.5 €/h for access and egress times and 75 €/h when waiting or transferring.

The operator's two main expenses are approximated by the averaged seat-km (marginal) values as identified Campos and de Rus (2009), which gives that $c^{oper,marg} = 0{,}130$ €/seat-km and $c^{main.marg} = 0{,}0122$ €/seat-km (which are both reduced by 20 % for the free market governance scenarios, as will be explained in *section 4.2*). Additional costs to be considered follow from the required number of vehicles to operate the network. These higher due to the improvement of a contingency factor of 1.1, a turn-around time of 30 minutes and limitation of operational time (18 hours/day)

Finally, 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*', '*well-to-tank*' and '*habitat damage*'. Considering each of these factors for the three relevant modes gives total values of $c^{ext}_{air} = 4{,}3$,$c^{ext}_{HSR} = 1{,}3$ and $c^{ext}_{car} = 12{,}1$, all in €-cent/pkm

Constraints: The parameterisation of the constraints (*section 3.1.4*) was focused on a balance betweem realism and freedom for the model. This resulted in minimum line length $ln^{str.min}_{l_k} = 200km$, a minimum number of stops $n^{stops.min} = 3$, a maximum round trip time $t^{rt,max} = 18h$ and a minimum frequency $f^{min} = 1$ for activated lines.

Demand Estimations: 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). However, three main challenges have to be overcome: firstly (1), the observed flows only represent traffic between airport-pairs, rather than city-pairs. Secondly (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. Thirdly (3) it should be noted that 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. Together, the operations produced an OD-matrix for long-distance travel demand between all of the 124 cities.

The demand estimation resulted in a total number of $2 \cdot 1{,}07 * 10^6$ trips per day within the network, with demands ranging between a maximum of $(2 \cdot 1{,}03 \cdot 10^4)$ and a minimum of $(2 \cdot 4{,}80 \cdot 10^{-}1)$ passengers per day per OD-pair. Across the network, flows were observed for 5.174 out of 7.688 possible OD-pairs. To decrease the computational burden of the problem, only the largest OD-pairs - together comprising 90 % of the network's demand - were considered. In this case, this resulted in all ODs having a demand smaller than approximately $2 \cdot 20$ passengers per day to be eliminated. Together, this made that only 985 OD-pairs had to be evaluated.

3.4. *Experimental Set-up*

Having a fully developed HSR-adaption of the TNDSFP and associated solution strategy, combined with a case-specific parameterisation, it became possible to initialise the model for research purposes. This section discusses the experimental set-up of this research. First, *section 3.4.1* presents the implementation characteristics and the performance that the model was able to reach in a small test. Following this, the results were validated on feasibility in *section 3.4.2*, which led to the retrospective introduction of strategic pricing. Finally, *section 3.4.3* sets out the expermiments that were performed to answer the research question.

3.4.1. *Model Implementation and Performance*

The implementation of the model and its solution strategy were written in '*Python 2.7.16*' using the environment of '*Spyder 3.3.6*', which was verified by continuous checks. All tests were performed using single personal computers with an Intel(R) processor, Core(TM) i5-8500, 3.00 GHz and 16 GB RAM memory. To evaluate this computational performance, the algorithm was executed for a smaller problem (Germany: seventeen cities, eighteen possible lines) and compared with an exhaustive search. The exhaustive search required 10.486 seconds to examine all possible line configurations, whereas the heuristic managed to reach this global optimum in 379 seconds, thus reducing the computational time by a factor 28. Further examination showed that using '*line activation*' only (operation 6. and operation 7.), it was possible to reach an objective value performance of 99.4 % in only 101 seconds, hence reducing the computational time by a factor 104.

Performing the simulation for a large scale problem (Europe: 124 vertices, ~2·5000 OD demand flows, ~7000 feasible lines), it was found that the computational burden became too large, with an estimated running of 70 years per simulation. To reduce the size of the problem, three previously mentioned measures were taken. Firstly (1), the number of lines was reduced by assigning 50 key-vertices (37 capitals and 13 cities important by geography or size, see mysectionLGPref); secondly (2), a further reduction was made by the strategic elimination of lines (-50 %, see mysectionLGPref) and thirdly (3), only the top 90 % of the demand was considered (see *section 3.3* on '*demand estimations*'. Together, the measures resulted in a problem of 124 vertices, with approximately 2·1000 demand flows and 350-400 possible lines. The heuristic search required approximately 3-5 days to complete these simulations, depending on the extensiveness of the final network.

3.4.2. Result Feasibility and Passenger Path Control

Using standard parameterisation (*section 3.3*),it was seen that simulations were not able to develop into an integrated network, leaving the continent with multiple not-connected sub-networks. Observing relatively high degrees of network completeness and direct passengers within these sub-networks, it was concluded that this standard parameterisation leads to a barrier which prevents the operator from connecting the sub-networks.

The cause for this behaviour was searched into two types of disadvantageous passenger paths: those that make a detour to avoid (1) geographical barriers (oceans/mountains) 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. To solve this, three possible solutions were proposed: (1) forceful subsidisation, (2) altering transfer characteristics (transfer time and the maximum number of transfers) and (3) strategic pricing (spilling unprofitable passengers).

Testing the potential solutions showed that all options contributed to a better network integration. Comparing the overall impact of the solutions, strategic pricing was considered to be most desirable due to its elegance, as it explicitly impacts the passengers of interest. This led to the inclusion of the infrastructural strategic pricing level constraint of *Equation 16* and the geographical strategic pricing level constraint of *Equation 15*. Analysis on these factors, as will further be discussed by *Table 5* in *section 4.3*, showed the effectivity of intensifying the exclusion of infrastructural detouring passengers to a value of $fac^{SPL,infra} = 1{,}05$. Opposed to this, the relaxation (up until $fac^{SPL,geo} = 1{,}25$) of the geographical detour exclusion constraint gave better results, meaning that the effectivity of this exclusion strategy cannot be confirmed. Additional to this, the same analysis demonstrated the positive impact of limiting the number of transfers to one. Regarding the alteration of transfer time, no pattern of for strategic passenger selection could be identified.

3.4.3. Experiments

With all previous steps, it becomes possible to perform experiments that can provide the insights that are necessary to answer the research question, that was concerned with the potential contribution of improved design for line configurations as well as understanding on how these networks look like. The analyses are structured under four experiments, that each consist of one or more strategically chosen scenario simulations. Below, an overview is given:

- **Experiment 1:** Estimation 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 and comparison with initial standard

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4. RESULTS

Results of the experiments as defined in *section 3.4.3* are stated in this chapter, to ultimately answer the research question. First *section 4.1* ('*Experiment I*)' presents the simulation of the initial network, such that later scenarios can be compared. Following this, *section 4.2* discusses the analysis on the impact of pricing and governance strategies ('*Experiment II*'). Continuing, *section 4.3* on '*Experiment III*' assesses the relative importance of the HSR design variables in vehicle characteristics, passenger paths restrictions and line design features. Finally, *section 4.4* ('*Experiment IV.*') constructs two synthesised scenarios based on learned lessons, which allows to determine the potential contribution and design characteristics of improved design for line configurations, when compared to the initial situation.

4.1. Benchmarking the Initial Performance

'*Experiment 1*' (defined in *section 3.4.3*) concerned the estimation of the network's performance and characteristics for the initial conditions, such that it could be used as a benchmark for further comparisons. These initial conditions were determined to be characterised by the standard case study parameterisation of *section 3.3*, the EU's believe in a competitive railway market (thus '*Free market*' governance structure) and a pricing environment where societal costs are not internalised ($\psi^{user} = 50$, $\psi^{operator} = 50$, $\psi^{society} = 0$). Both of these governance and pricing strategies are further contextualised in *section 4.2*.

The results of the simulated network are stated in the first '*Initial*' column of *Table 6* (descriptive KPIs) and *Table 7* (stakeholder-financial KPIs). An analysis of these number indicates that this scenario has been able to develop into a well functioning HSR system, given its positive cost-benefit ratio of € 24.9 million per day and its considerable HSR-trip substitution of 14.7 %. However, fluctuating behaviours were observed when visually analysing the network. It reached all parts of the network to a certain extent, with 89 of124 cities connected), but still experienced difficulties in connecting sub-networks despite the introduction of strategic pricing (*section 3.4.2*). Something that is confirmed by the low share of transfer passengers ($t_1 = 7{,}5\,\%$, $t_2 = 0{,}5\,\%$). This first simulation is not yet enough to define the typical characteristics of an HSR system, but should rather be seen as a lower boundary for later comparisons. A further analysis of the network's characteristics is stated in *section 4.4.2*.

TABLE 4: 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

4.2. *Effects of Pricing and Governance Strategies*

To test the effect of different pricing policies and governance strategies, six diverging scenarios (see top rows of *Table 4*) were simulated in '*Experiment 2*' (see *section 3.4.3*). 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*' (sc. 3,4,5,6), 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 subsidisation/taxation of societal costs (sc. 4,5,6). Combining the governance and pricing strategies gives twelve potential scenarios. However, given the unlikeliness of heavily subsidised private entities or neglected societal costs in centralised systems, a selection was made. The observed relations to the KPIs for altering design variables are given in *Table 4*.

Governance: Isolating the divergent characteristics of governance strategies, as can best be seen in scenarios 2 and 3, indicates a stronger cost-efficiency of a free market (total benefits), whilst offering relatively similar extensiveness (RPK, no. of lines, connected vertices) 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. However, it should be noted that the magnitude of this difference follows the arbitrary reduction of 20 % in operator costs, although this nevertheless indicates a relatively substantial increase of efficiency for a small compromise in network performance.

Pricing: Concerning differences in pricing policies, it is seen that the internalisation of external costs induced a strong growth in the extensiveness (ASK, RPK, number of transfer passengers) and the performance (user & societal benefits) of the network. However, mixed results were found for the ratio between costs and benefits (thus total benefits). In the free market scenarios (1,2), 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), which induces a better cost-benefit ratio. For the centralised scenarios, different behaviour is seen. Enlarging the interests of users or society leads to the inclusion of lines that are not necessarily the most cost-efficient, but that do contribute to the pursued policy goals (sustainability, mobility or social cohesion). The reduction in total benefits is a lot smaller than the increase in user and societal benefits, indicating a positive rate of return, which will be further elaborated in *section 4.4.3*.

4.3. *Importance of HSR Design Variables*

To define the importance of design variables, an analysis was performed on multiple parameter settings in '*Experiment 3*' of *section 3.4.3*. An overview of the observed relations is displayed in *Table 5*. The studied parameters are stated on the vertical axis, whereas the effect on KPIs, as related to goals associated with HSR, are stated on the horizontal axes. The relation values in the table indicate the average expected change for the base value of the KPI when changing the design variable by the defined interval. An exemption applies to those values that reached a peak value (optimum), which are indicated with an asterisk. Here, the KPI changes with the relation value by every interval step from the peak. Below, the vehicle, line and passenger path features are discussed.

Vehicle Characteristics: Altering the characteristics of high-speed trains resulted in the unambiguous patterns of the first to rows in *Table 5*. Increasing the cruising speed allows for a higher level of service, thus contribution to all policy goals. Opposing to this, a higher seating capacity makes it harder for the operator to accurately assign capacity, resulting in a lower performance and a smaller

TABLE 5: MEASURED RELATIONS BETWEEN HSR DESIGN VARIABLES AND KPI CONTRIBUTION TO POLICY GOALS

						Operator (cost-efficiency)				User (mobility)			User (soc. cohesion)			Society (sustainability)		
	Parameter	**Unit**	**Range**	**Interval**	**Base→ Peak* ↓**	**Total costs savings** € $2-2{,}5\cdot10^7$	**Operator costs** € $2-3{,}5\cdot10^7$	**Avg. load factor** $60-65\,\%$	**Share transfer pax** $10-20\,\%$	**User costs savings** € $3-4\cdot10^7$	**APK HSR** $275-625\cdot10^6 km$	**Share direct pax** $80-90\,\%$	**No. connect cities** $90-115(of124)$	**Reachable ODs** $400-1150(of1300)$	**No. of lines** $50-90$	**Societal costs savings** € $1-1{,}5\cdot10^7$	**RPK HSR** $175-375\cdot10^6$ km	**% HSR** $15-30\,\%$
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
	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*
	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
	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
	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*
	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*
	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
	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.

network. Both effects for vehicle speed and capacity an be expected to be tempered in further and 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 5* present the adjustments in the lines that compose '*Pool of Lines*' (*section 3.2.2*), from which the model was allowed to select lines. The most important observation regards the usage detour. Here it is seen that the inclusion of slightly demand-based lines in the LGP ($fac^{dt,dm} = 0{,}125$) is beneficial to most user and societal goals, although it also comes at the cost of operator efficiency. Further examination highlights the performance peak when constraining the minimum number of stops to three (two terminal stations and one intermediate) per line, though it should be mentioned that 2-stop lines might still be beneficial when added to the pool of lines, as they currently mostly replace 3-stop lines following the character of the line reduction of *section 2*.

The alteration of the infrastructural line detour constraint (*Equation 9*), an optimum at the a value of $fac^{dt,infra} = 1{,}50$ was found. Here, a lower factor would mainly exclude beneficial routes (given the reduced network development) and higher factor would result in a lower operator efficiency (given the larger number of lines between a smaller number of vertices). Finally, the geographical line detour constraint (*Equation 10*) showed to be nonrestrictive when set at $fac^{dt,geo} = 1{,}50$. Intensifying to $fac^{dt,geo} = 1{,}25$ resulted in a deterioration of both the descriptive KPI performance, as well as the cost-efficiency, thus indicating that it is best to disregard this constraint.

Passenger path features: In *section 3.4.2*, 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 5*.

4.4. *Potential Impacts of Improved Design*

The final experiment, '*Experiment 4*' as defined in *section 3.4.3*, uses the lessons from previous experiments to determine the typical design characteristics and potential impact of improved HSR line configurations. First, *section 4.4.1* defines these improvements to be made. Following this, *section 4.4.2* analyses the resulting networks on their lay-out to find how a typical strong-performing network looks like, after which the *section 4.4.3* concludes by examine and compare performance that the networks are able to provide to each stakeholder.

4.4.1. *Proposed Synthesised Network Settings*

To assess the potential contribution of a well-designed HSR system in the European context, two synthesised scenarios were defined and tested. These scenarios find their base in the standard parameterisation of *section 3.3* - as this tried to describe reality - but are adjusted for the lessons learned from the previous analyses, which are comprised in the following adjustments: First of all, both scenarios were limited to a maximum of one transfer per path, whilst the geographical detour path constraint of *Equation 10* was released. Furthermore, it was chosen to set the geographical strategic pricing level to the tested upper limit ($fac^{SPL,geo} = 1{,}25$) and the infrastructural strategic pricing level to the tested lower limit ($fac^{SPL,infra} = 1{,}05$)

The first scenario, '*Economical*', described a low-effort solution that aims for a high cost-efficiency. This holds a '*free market*' governance structure (-20% operator costs) with an equal distribution of objective function weights, thus $\psi = 33{,}3$ for all stakeholders. moreover, this scenarios is characterised by a shortest path-based lines only ($fac^{dt,dm} = 0{,}00$). The second scenario, '*Extensive*', works from a '*centralised*' governance structure (-50% transfer time), which is actively subsiding for user and societal benefits ($\psi^{user} = 37{,}5$, $\psi^{operator} = 25{,}0$, $\psi^{society} = 37{,}5$). Here, the pool of lines is supplemented with demand based-routes ($fac^{dt,dm} = 0{,}125$). The results of the simulated network are stated

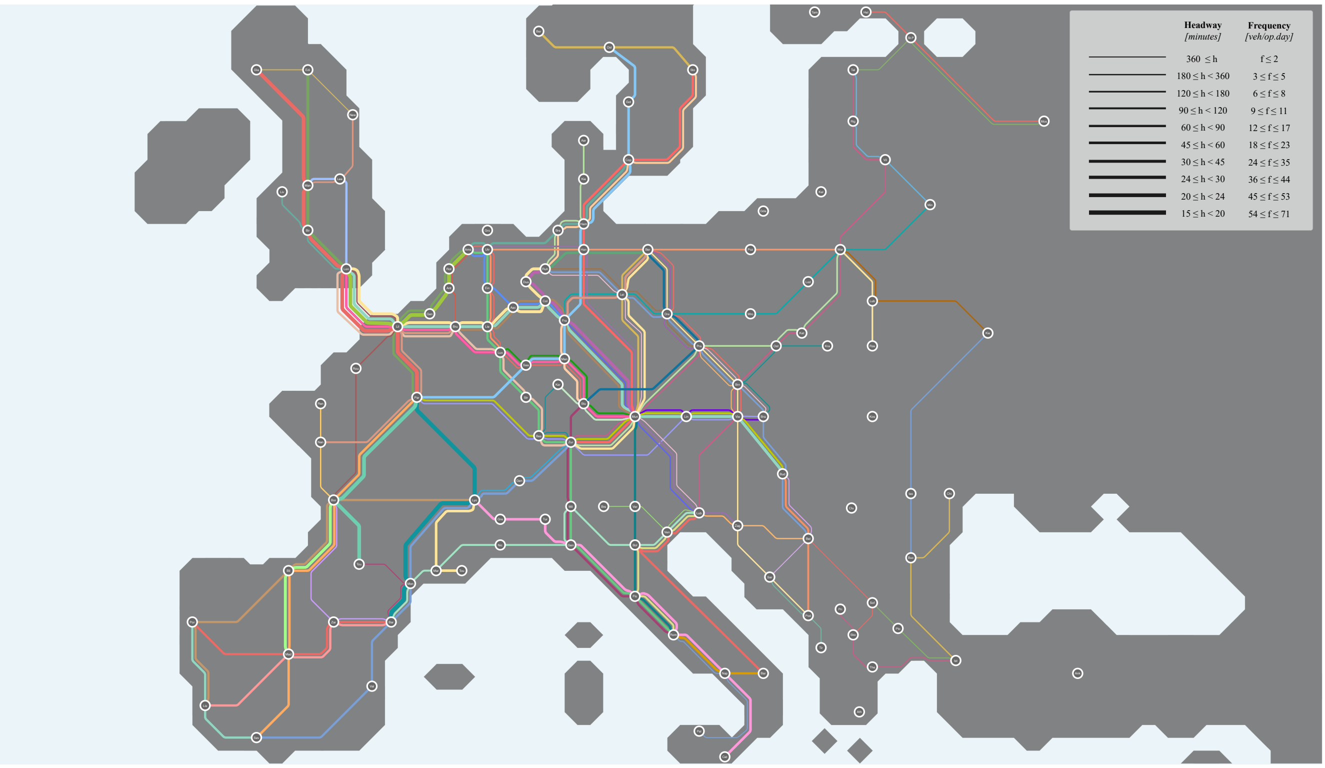

Fig. 5: Transit map of the extensive HSR network

in the second '*Economical*' and third '*Extensive*' column of *Table 6* (descriptive KPIs) and *Table 7* (stakeholder-financial KPIs). These values are used as a basis for further analyses.

4.4.2. *Design Characteristics of Resulting Networks*

The simulation of the initial (*section 4.1*) and improved (*section 4.4.1*) networks led to the observation of multiple recurring patterns in their network design. All scenarios resulted in functional high-level 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 5*, where colours are used to distinguishes for lines and where widths indicate their 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.

Network design: All three simulations have a development of lines throughout the continent, but also show a similar decisions on the exclusion of cities or regions that don't justify connections because of their demand or geographical characteristics, as can for example be seen in in *Figure 5*. Visually analysing the networks resulted in tree main aspects. Firstly (1), it is seen that 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. Secondly (2), it was observed that the network extensiveness and density are slightly skewed to the west, given the lower demand in Eastern Europe. Thirdly (3), it was seen that 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: In the observed networks, four recurring line types were distinguished: First (1), all networks accommodate 5-20 (depending on the extensiveness) relatively long lines (length >1000km; 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 this, the majority of lines have a shorter profile (length <1000km), 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) line category concerns lines that produce enough demand by themselves, which means that they are found in both low- and high-density areas. Finally, a fourth (4) category is described as 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. An overview of line characteristics is found in the middle rows of *Table 6*.

TABLE 6: SYNTHESIS NETWORK CHARACTERISTICS

	Unit	Initial	Economical	Extensive
Number of lines	[-]	54	83	91
Connected vertices	[-]	89	110	116
Reachable ODs	[-]	396	944	1148
Min. line length	$[km]$	272	200	200
Avg. line length	$[km]$	738	834	831
Max. line length	$[km]$	1747	2039	1950
Min. no. stops/line	$[seats]$	3	3	3
Avg. no. stops/line	$[seats]$	4.00	4.6	4.7
Max. no. stops/line	$[seats]$	11	12	12
Min. freq./line	$[veh/day]$	1	1	1
Avg. freq./line	$[veh/day]$	9.2	9.1	11.0
Max freq./line	$[veh/day]$	37	47	65
Available seat km	$[10^6 km]$	277	499	633
Revenue pax km	$[10^6 km]$	168	300	378
Avg. load factor	$[\%]$	60.5	60.0	59.7
Modal split air	$[\%]$	62.1	56.5	53.5
Modal split HSR	$[\%]$	14.7	25.0	29.9
Modal split car	$[\%]$	23.2	18.5	16.7
Avg. HSR trip dist.	$[km]$	488	558.3	589.9
Share direct pax	$[\%]$	92.0	87.5	77.8
Share 1-trf pax	$[\%]$	7.5	12.5	22.2
Share 2-trf pax	$[\%]$	0.5	*n/a*	*n/a*

4.4.3. *Potential Contribution of Improved Networks*

To find out how - and 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. This is done by first assessing the resemblances and differences on the multi-aspect performance by the descriptive KPIs, after which the financial-benefit implications for the three main stakeholders are examined.

Geographically dependent performance: The vertex and edge characteristics, resulting from the line configuration of the extensive scenario, are presented in *Figure 6*. In this map, the daily vehicle loads per edge, magnitudes of HSR traffic per city and modal split changes are provided. 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, but should also be sought in the model's limitations of limited pool size (where the line would ideally be one leg shorter, but which is not available) and the neglection of the smallest demand flows. It is seen that these practices are similar across the scenarios, relative to their extensiveness.

Variations of network extensiveness: Differences in the three networks were identified by extracting and assessing the descriptive KPIs, as presented in *Table 6*. The lower rows of this table show unambiguous results for a further network development along the scenarios. This is primarily confirmed by the increased revenue passengers kilometres (RPK; +26 %) and available seat kilometres (ASK; +27 %) when comparing the '*Economical*' to '*Extensive*' strategies; effects that are even bigger when comparing the '*Initial*' to '*Extensive*' scenarios, with a growth of +125 % for the RPK and +129 % in ASK. The higher connectivity values (number of lines, connected vertices and reachable OD's), as well as the increased

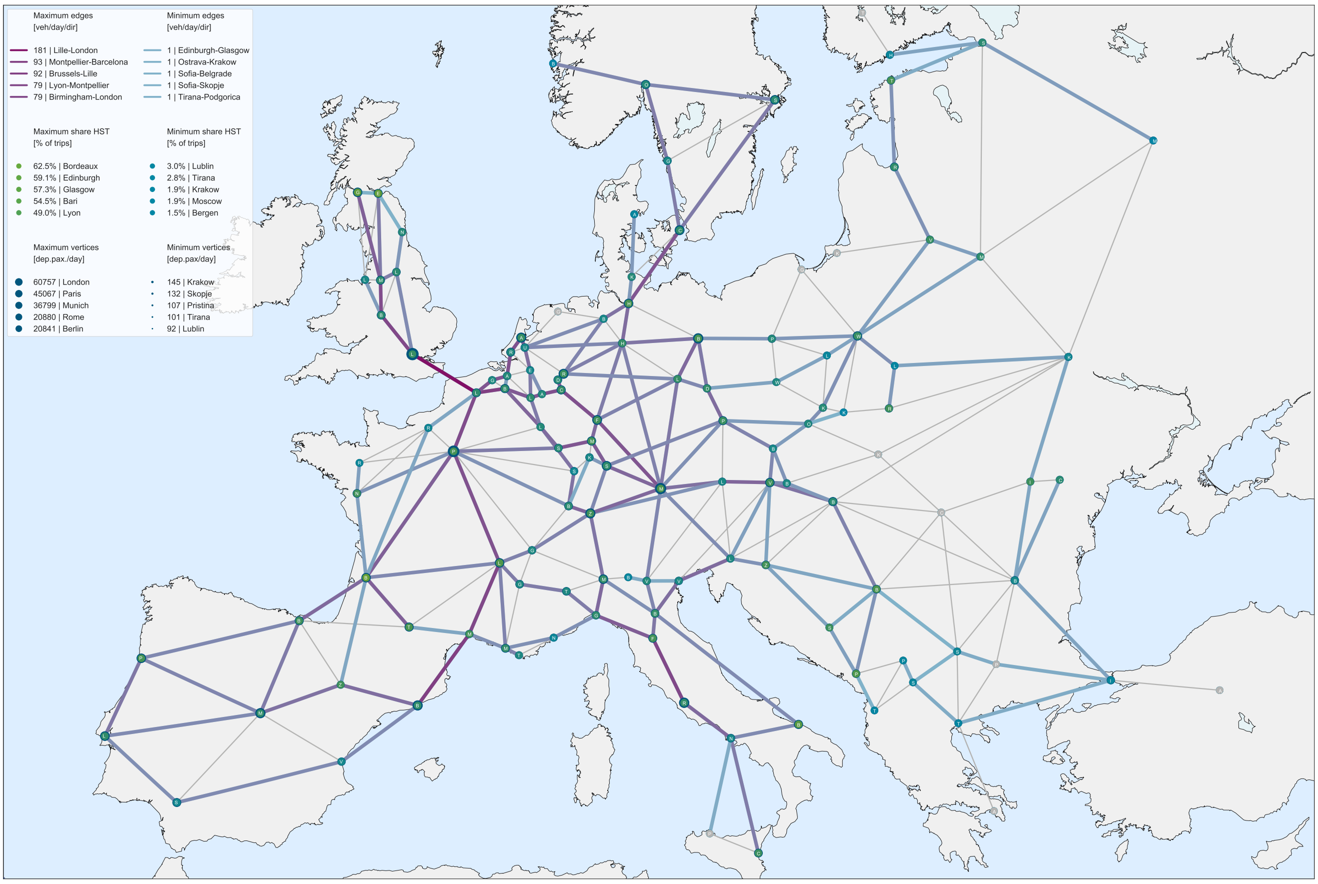

Fig. 6: Network characteristics of the extensive HSR network

share of transfer passengers, indicate that the above growth comes from a more wide-spread and integrated network. More transfer passengers would logically have positive results on the train occupation. However, a slight decrease of the average network load factor (ANLF) is observed (‘*Economical*’: -0.8 %; ‘*Extensive*’: -1.3 %). This behaviour explains that the model has accepted less profitable routes (thus less competitive with other modes or fewer justification of train capacity) when internalising external costs, as it prioritises the benefits of users and society over the operator’s interests.

Differences in induced modal shifts: Considering the competition with other modes, 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 distribution of this substitution is plotted in *Figure 7*, which shows that the HSR is especially competitive between 400-600 km. 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. Something which is confirmed by the increased average HSR trip distance (+5.7 %) in *Table 6*. This behaviour can be explained by the better network integration and coverage which allows for ease of travel on longer trips, but should also be sought in the underlying costs aspects. Therefore, a further analysis on these costs is done in the paragraph below.

Cost aspects and stakeholder benefits: To assess the previously mentioned costs aspects, the total expenses and benefits were separated for each stakeholder, further divided in subcomponents and presented in *Table 7*. 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 when applying the extensive scenario, as the costs associated with waiting times increase the most.

Concerning the societal (external) costs, the most substantial benefits of substitution towards HSR are found within the fields of accidents, congestion and climate. Especially the first two of these have a strong relation to the modal shift from the car, as high costs on these factors are characteristic of road traffic. This is confirmed when categorising the societal benefits per mode, which in a reduction of external costs that was mainly induced by substitution from car traffic (72 %) as opposed to air traffic (28 %). Together, the above indicates that, when aiming for larger societal benefits, most is to be won in the competition with automobile traffic. This also leads to the finding that most societal benefits are won in externalities of car traffic, which are not only environmentally related. *Table 7* shows 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 than what is most frequently argumented.

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*’, mainly due to a sharp increase of operator costs, though still better than the ‘*Initial*’. This reduction compared to the ‘*Economical*’ scenario is primarily explained by the lower load factor and the inclusion of less profitable lines.

Comparing the overall costs of the two improved scenarios, it is seen that the increase of user and societal benefits reaches 10.7 million euros per day. At the same time, this comes with a deterioration

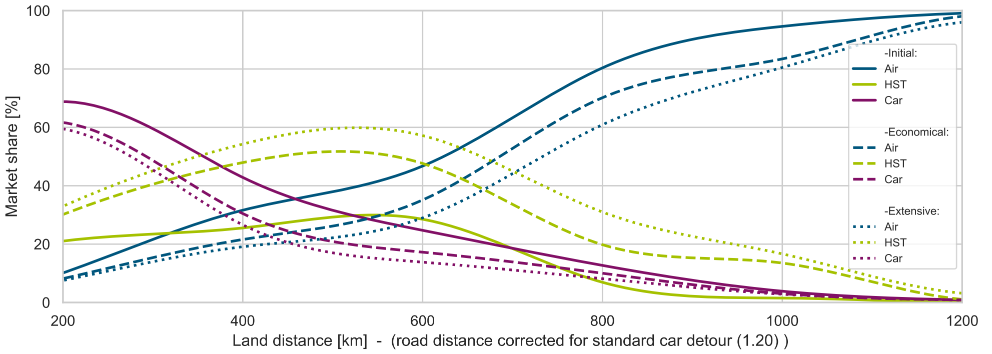

Fig. 7: Modal split per distance

of 5.9 million euros per day on the cost-benefit ratio. Combining these two values gives a rate of return reaching 1.8 when opting for active subsidisation with the defined weights and a centrally organised network. This effect can be expected to be even more substantial when considering secondary benefits of these policy goals. Concluding on that, it means that it should be a political decision whether the performance advantages outweigh the increased subsidisation costs and efforts for centralising and taxing.

TABLE 7: COST COMPONENTS OF SYNTHESISED SIMULATIONS

		Initial	**Economical**	**Extensive**
			All in [10^6 € per day]	
User	**Access & Egress**	3.0	4.0	5.1
	Waiting	-19.4	-28.7	-36.1
	In-vehicle	-16.5	-28.0	-30.0
	Transfers	1.9	4.7	5.4
	Sub-total	**-31.0**	**-48.0**	**-55.5**
Operator	**Operational**	14.7	25.8	41.0
	Maintenance	1.1	2.7	4.0
	Sub-total	**15.8**	**28.4**	**45.0**
Society	**Accidents**	-3.2	-5.1	-6.2
	Air pollution	-0.7	-1.2	-1.5
	Climate	-2.5	-4.4	-5.5
	Noise	-0.3	-0.5	-0.5
	Congestion	-3.1	-5.0	-6.0
	Well-to-tank	-0.5	-1.0	-1.2
	Habitat damage	0.6	1.0	1.5
	Sub-total	**-9.7**	**-16.2**	**-19.4**
Total costs (societal costs-benefit)		**-24.9**	**-35.8**	**-29.9**

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.

Performing the above, this research contributed to the current state of knowledge in the field of HSR network design, by the exploring the interface of the research fields comprising HSR broad, general transit planning and strategic network planning research. Together, this ultimately led to the development of an HSR-adapted TNDFSP model, which was demonstrated to be useful for more specific design questions. With this, new ways were opened for further research and thus further understanding of HSR network design.

This study found, in *section 4.2*, that the internalisation of actual 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, resulting in a positive rate of return as demonstrated for the European case in *section 4.4.3*.

Regarding the features of lines, it was seen in *section 4.4.2* that typical improved network designs comprise a certain number of longer (1000km-2000km) and high frequency (>18 veh/h) lines, socalled '*main arteries*', often connecting multiple countries within the continent. The presence of such lines illustrates 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 point of perspective. Both arguments plead for overarching design view, as history has shown that a lack of knowledge on HSR design and the national and company interests resulted in a patchwork of poorly connected sub-networks.

Following this, strategic pricing - thus the exclusion of unprofitable passengers by limiting the number of transfers and spilling certain detouring passengers - turned out to be indispensable for the development of a functioning HSR network, as demonstrated in *section 3.4.2* and numerically analysed in *section 4.3*. Such a pricing system requires a coordinated approach and therefore again benefits from improved cooperation.

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. All in all, the decision for different governance and pricing strategies could be argued in multiple perspectives. However, the findings of this study shed a new light on the current practice and provide political discussion with additional arguments on how to design the most successful European HSR system.

Valuable further knowledge could be gained by future research that generically explores the vertical axis of transit planning, thus including - for example - the construction of infrastructure on one side, or the introduction of heterogeneous vehicles, the adaption of operational strategies or the inclusion of multi-modal trips on the other side. Additionally, knowledge in the field of this specific study could be enhanced by more diverse case studies, a higher detail level within the case or the introduction of innovative technologies.

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