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Service design and frequency setting for the European high-speed rail network

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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, a European HSR-network is yet to be realised, with the current state amounting to a patchwork of poorly connected subnetworks. Consequently, this results in a suboptimal performance from a user, operator and societal perspective. We present a customised version of the Transit Network Design and Frequency Setting Problem (TNDFSP) for the long-distance transport context and HSR in particular. We apply an adapted version of a heuristic solution approach to analyse the users', operators' and societal performance of a European HSR-network by conducting an extensive series of experiments to test the network's performance under various policy priorities and HSR design variables. Our experiment results show that designs resulting from the consideration of externalities yield more extensive networks with larger coverage and modal shifts. For such networks to materialise, high public investments are needed. The obtained network designs contain four different line types, exhibit spatial disparities in network density, and allow for the identification of potential hubs and critical infrastructure. The strong network integration with overlapping and border-crossing lines of substantial lengths highlights the importance of cross-border cooperation and rail interoperability. We hope our findings will contribute to the ongoing public and professional debates on designing an attractive and competitive European HSR-network.

1. Introduction

Long-distance travel has become increasingly common in the past century (The World Bank, 2020). While bringing many advantages by means of enhanced mobility and connectivity, it also comes at a cost due to the externalities generated, such as the depletion of finite natural resources, noise pollution and its contribution to climate change (Janić, 1999). High-Speed Rail (HSR) is often considered a promising alternative for short-haul flights (<1500 km) and long-distance car travel (>200 km) since it may offer competitive services while inducing fewer environmental disadvantages (Albalate & Bel, 2012). Fraszczyk et al. (2016) concluded in

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their evaluation of rail systems performance in Europe that "*the rail system is not preparing for the increase in the number of passengers meaning that the performance of the rail system as a whole will suffer due to this lack of foresight*". This has recently motivated commitments for large-scale investments in developing a European HSR-network (European Commission, 2020). However, infrastructure investment alone is insufficient to provide a better international train service (Witlox et al., 2022).

Despite the seemingly favourable circumstances, a European HSR-network is yet to be realised. While much of the infrastructure already exists, the current network is a patchwork of poorly connected subnetworks without good cross-border coordination (European Court of Auditors, 2018). This suboptimal state can be attributed to two intertwined underlying problems: (1) lack of knowledge to form a system perspective and vision on the design of line configurations for High-Speed Rail at an international network scale and (2) poor network integration due to the prioritisation of national and railway company interests (Raad voor de leefomgeving en infrastructuur (Rli), 2020). In the following, we primarily contribute towards the former but thereby also gain insights into the second.

Our research addresses the following 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 policy priorities, and what would such networks look like?*". To this end, we solve the Transit Network Design and Frequency Setting Problem (TNDFSP) as described by Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009) and Ibarra-Rojas et al. (2015) for the European HSR-network. This research is the first attempt to solve this problem, which is typically applied in an urban or regional context. The resulting network design patterns and network performance assessment under a range of scenarios constitute a substantive contribution of this work. Notably, while most studies devoted to variants and applications of TNDFSP have assumed passenger demand to be inelastic (i.e. service design is assumed to impact route choice and thereby flow distribution but not mode choice), this assumption cannot be reasonably applied to the long-distance travel market. Therefore, we are particularly interested in the impacts of HSR service design on modal split. In the context of HSR and long-distance travel, plane and car are the most important travel alternatives. We, therefore, need to obtain the relevant travel time attributes for each origin–destination combination for travelling by car, train and plane. The latter two involve identifying the set of international train stations and airports – which are provided as input to the problem – that are reachable from the origin city and destination city and then searching for mode-specific path alternatives, including those involving transfers. We formulate an objective function consisting of users' (of all modes), operators' and society's perspectives. The model's adaption for the HSR setting primarily involves the integration of (competing) modalities and their respective travel attributes (access, egress, transfer attributes), long-distance travel demand characteristics (calibrated using air travel flows), passenger behavioural aspects (e.g. maximum transfers and detours) and policy assessment (e.g. considering seven main externalities for long-distance travel) and policy options (scenarios and sensitivity analyses in relation to European development goals) relevant in the HSR-context.

The remainder of this paper is organised as follows: Section 2 provides a brief overview of relevant studies, particularly their relevance to the HSR-context. We then describe the design problem addressed in this study and the methods used to solve it in Section 3. Following this, Section 4 presents the parameterisation of the European case and model implementation. Next, in Section 5, we present the results of the performed experiments and discuss the main lessons, after which conclusions are drawn in Section 6.

2. Related work and modelling considerations

In the following, we briefly review the literature in the strategic transit design field. The literature on the Transit Network Design and Frequency Setting Problem (TNDFSP) is vast and well-established, and the interested reader is referred to the excellent reviews by Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), Farahani et al. (2013) and Durán-Micco and Vansteenwegen (2022). In the recent survey by Durán-Micco and Vansteenwegen (2022), they concluded that while the problem is in principle applicable to other modes, the literature is dominated by urban bus networks. Only a handful of the works included in the review are concerned with metro or regional train services, and only one, namely Liu et al. (2020), is devoted to the HSR network. Liu et al. (2020) developed a profit-oriented objective for the Chinese HSR, and passenger demand is considered constant and exogenously determined. In contrast, the objective of our study is to estimate the share of demand and thus passenger volumes that will choose to travel by HSR in the presence of long-distance travel alternatives such as car and plane. Therefore, we focus on critically assessing the available techniques in terms of their potential for designing HSR where demand is considered endogenous to the TNDFSP and related challenges.

2.1. Problem formulation

Ideally, all aspects of a transit network would be designed simultaneously. However, due to the highly complex working environment and the extensive range of stakeholder interests, the problem is frequently divided into smaller sub-problems. The set of formulations that quantitatively describe these problems can be grouped under the overarching title 'Transit Network Planning Problem' (TNPP) (Ibarra-Rojas et al., 2015). Guihaire and Hao (2008) propose a framework to categorise TNPP-problems combined with other related planning problems. The topic of our study - centrally designed HSR line configurations - can be classified into the 'Transit Network Design and Frequency Setting Problems' (TNDFSP) category. The TNDFSP combines a (1) *'Network Design Problem'* (defining a set of lines consisting of terminal stations and intermediate stops) with a (2) *'Frequency Setting Problem'* (finding adequate time-specific frequencies) for a given demand. The resulting output of the two combined problems consists of a *'Line Plan'* and the associated *'Frequencies'*. Together, they form the *'Line Configuration'* (Kepaptsoglou & Karlaftis, 2009; Schöbel, 2012).

The TNDFSP is formulated as an optimisation problem and, as such, consists of four components: (i) input parameters composed of network and demand characteristics, (ii) objectives, (iii) decision variables and (iv) constraints. In the following, we discuss each of these ingredients to be defined and specified in tailoring the TNDFSP to the HSR context.

Network Characteristics. The network representation used in TNDFSP consists of '*nodes*' (vertices, stations), '*links*' (edges, direct connections between nodes), '*lines*' (services on connected links) and '*paths*' (passengers between two nodes following lines) (Schöbel, 2012). Allard and Moura (2014) and Lovett et al. (2013), who studied HSR-related design problems, used an irregular (grid) structure attempting to reflect the fact that spatial geography on longer distances typically follows an irregular pattern when compared to urban regions. The size of the structures they analysed was relatively small, up to 10 nodes. Jong et al. (2012) combine the strategic frequency setting problem with a tactical timetabling problem, arguing that the infrastructural limitations of (high-speed) rail infrastructure are such that time-dependent considerations are critical.

Demand Characteristics. Based on past work, we identify three main aspects of demand modelling in TNDFSPs: (1) two distinctive '*Spatial patterns*' are considered: a '*one-to-many*' demand pattern (focus is on one node, e.g. Chien and Schonfeld (1998)) and a '*many-to-many*' demand pattern (emphasising flows at a network scale, e.g. Hassan et al. (2019); (2) the '*time horizon'* varies between years for the construction of infrastructure and minutes for tactical and operational problems (Farahani et al., 2013; Ibarra-Rojas et al., 2015), and (3) differences in '*Behavioural responses'* are observed. The latter can be subdivided into '*fixed or elastic total demand*' (when considering generation effects) and '*fixed or elastic mode-specific demand*' (when evaluating modal substitution). For an analysis of the TNDFSP in the context of HSR at the European level, it is considered that a '*many-to-many*' demand pattern and a longer '*time horizon'* are required. Furthermore, it is considered important to account for '*elastic mode-specific demand'* to capture the impacts of alternative designs on the market share of HSR.

Policy objectives. The TNDFSP may be formulated as a multi-objective problem in which each component reflects the interests of a key stakeholder. Typically, transit planning has two main partners involved with diametrically opposed interests: operators wishing to minimise their costs and users desiring a minimisation of their travel impedance (e.g. travel time, costs, transfers) (López-Ramos, 2014; Owais et al., 2016). Some studies expand these stakeholder interests by incorporating a broader set of goals, such as the minimisation of externalities generated (Li et al., 2013) or combining multiple objectives to yield total (societal) welfare (Gallo et al., 2011). The latter is highly relevant for the HSR-context given the complex long-distance context and the interests transcending those of a single planning authority.

Decision Variables. In the majority of studies, two primary decision variables are considered in the TNDFSP formulation: (1) '*line selection*' and (2) '*line frequencies*'. These variables are sometimes expanded to include characteristics such as the seating capacity, service level, fares, and pricing levels (Kepaptsoglou & Karlaftis, 2009). Note that the outcomes of 'line selection' and 'line frequencies' also determine route length, stop sequence, service directness or the lack thereof (Fan & Machemehl, 2008).

Design Constraints. Imposing constraints on optimisation problems ensures the yielding of realistic solutions and helps reduce computational requirements. Schöbel (2012) identifies constraints which mainly concern budget, capacity and connectivity requirements. López-Ramos (2014) also considers express services, the inviolability of existing lines and the time horizon to finish tasks. Zhao and Zeng (2006) focus on conventional bus systems and specify constraints pertaining to line design constraints, such as directness, length, shape and load factor. In contrast, the design of rail transport is dominated by its infrastructure and subsequent requirements. This results in additional constraints pertaining to physical interoperability and safety systems, more complex station or link capacities, difficulties in overtaking, and political factors (Yue et al., 2016). The fuzzy nature of the latter implies that they cannot always be quantified and, therefore, explicitly accounted for as part of the problem formulation. This research focuses on the strategic planning of HSR line design rather than operational considerations.

2.2. Solution strategies

TNDFSPs are often considered complex problems. Past studies (Baaj and Mahmassani, 1991; Fan, 2004) identified six main factors of complexity: (1) formulation 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 stochastic nature of variable transit demand. Schöbel (2012) observes that this problem often has an application-driven character, resulting in a large variety of problem formulations and solution approaches. Kepaptsoglou and Karlaftis (2009) define the two most fundamental strategies as the '*Line Generation & Configuration*' and the 'Line Construction & Improvement' methods. In the former, a set of candidate lines is generated and a sub-selection is made for the final network. In contrast, the latter starts with an initial line plan which is then subject to a step-wise improvement by making amendments to the lines' definitions.

The process of solving these problems follows either '*conventional techniques*' (analytical and mathematical programming) or '*heuristic techniques*' (heuristics and metaheuristics) (Iliopoulou et al., 2019; Kepaptsoglou & Karlaftis, 2009). The application of conventional techniques is generally considered less suitable because the problem is NP-hard, with past studies solving analytically simplified or highly constrained versions of the TNDFSP.

Various heuristic and meta-heuristic techniques have been deployed for solving the TNDFSP. Heuristics mostly use '*constructive strategies*' (skeleton, end-node assignment and network), which are applied in either a successive or a simultaneous order (Quak, 2003; Iliopoulou et al., 2019). The wide variety of applied techniques points to the importance of customised approaches.

3. Transit network design and frequency setting method for high-speed rail

We first describe the customised version of the TNDFSP (Section 3.1) for our HSR design problem, followed by a description of a novel heuristic that strategically searches the solution space for strong-performing results within a reasonable computation time (Section 3.2).

3.1. Problem formulation and related assumptions

In the following, we consider the strategic planning decision of determining the set of lines for an HSR-network and their respective service frequencies. Modelling assumptions were made to match the strategic character of this research, simplify the problem, maintain reasonable computational efforts, deal with limited knowledge in the novel HSR research field and underline the research goal. The list below summarizes the key assumptions:

- The number of trips between each origin and destination is fixed (no induced demand) and symmetric.
- The modal split of travel demand is based solely on the total travel time associated with each of the alternative travel modes.
- The network is assumed subject to a single central planner. Consequently, we neglect competition amongst service providers and the resulting ticket prices.
- Passenger trips are performed by either car, HSR (consisting of a maximum of two transfers) or air (using direct connections), each of which is also associated with local/regional access/egress legs.
- Travel flows are distributed across the network using a probabilistic and uncongested user equilibrium.
- The fleet of vehicles per mode is homogeneous.
- Rail traffic restrictions and strategies that may be deployed in tactical or real-time operations are not considered.
- HSR infrastructure is assumed to be interoperable and free from capacity restrictions.

The network is expressed as an undirected and incomplete graph $G(S, E)$, where the node set S represents city centres and rail stations, and the link set $E \subseteq S \times S$ represents direct connections between nodes. A rail line l is defined by a sequence of stations $l = (s_{l,1}, s_{l,2}, \cdots, s_{l,|l|})$, and the set of all lines is denoted L. We let $e \in l$ denote that link e belongs to line l, i.e. it is traversed by the respective path, $e = (s_{k,i}, s_{l,k+1})$ for some k. A line is thus defined as a service corresponding to a path in the graph, i.e. a sequence of directly connected nodes. Each link $e \in E$ may be operated by one or more rail lines. Thus, each link e is associated with the set of lines $L_e = \{l \in L | e \in l\}$ traversing the link.

Travel demand is connected to the network through a subset of origin–destination (OD) nodes, $S_{OD} \subseteq S$, which correspond to city centres which play the role of demand centroids. Links connecting these nodes and other – airport or rail station nodes - correspond to access and egress connectors. The overall travel demand is considered inelastic while allowing for modal shifts. Consequently, the HSR-specific OD-matrix depends on network characteristics, i.e. the attractiveness of the HSR alternative as compared to the car and air travel alternatives. Passengers travelling the HSR network using a single line follow a *direct path,* and passengers with a transfer follow a *transfer path*. This study is concerned with determining the two main arrays of decision variables of a typical TNDFSP: the set of lines, defined as the selection of lines to be active, and the associated frequencies.

Our objective is to minimise the weighted costs encountered by the three main stakeholders: Users, Operators and Society. The weights reflect the policy-maker trade-offs. This results in the objective function of Eq. (1):

$$MinZ = \Psi^{users} \bullet C^{users} + \Psi^{operator} \bullet C^{operator} + \Psi^{society} \bullet C^{society} \tag{1}$$

Here, Z is the objective function value, Ψ is a weight assigned to a stakeholder, i.e. users, operator or society, and C^x corresponds to the total costs encountered by the respective stakeholder.

The user costs correspond to the monetised travel time (monetised using the Value of Time, indicated as *VoT*), as formulated in Eq. (2). Each user's objective is to minimise travel time costs, and the assignment solution corresponds to user equilibrium. A passenger journey (mode- and route-dependent) consists of five cost elements: *access* (a), *waiting* (w), *in-vehicle* (h), *transfer* (n) and *egress* (g) times.

$$C^{users} = VoT\left[\beta^a \sum_m \sum_v \left(q^a_{v,m} \bullet t^a_{v,m}\right) + \beta^w \sum_m \sum_v \left(q^w_{v,m} \bullet t^w_{v,m}\right) + \beta^h \sum_m \sum_e \left(q_{e,m} \cdot t^h_{e,m}\right) + \beta^n \sum_m \sum_v \left(q^n_{v,m} \cdot t^n_m\right) + \beta^g \sum_m \sum_v \left(q^g_{v,m} \bullet t^g_{v,m}\right)\right] \tag{2}$$

The total user costs are the summation of the products of all time attributes t experienced by the volume of passengers q across the network and their respective *VoT* in the generalised travel time cost function. β's are the value-of-time coefficients for different travel attributes. Access, waiting, transfer and egress time costs incur at specific nodes $v \in V$ and flows are distinguished based on paths originating, destined, traversing or interchanging at the respective nodes, whereas in-vehicle time costs are associated with traversing specific links $e \in E$. Links and nodes are associated with a particular travel mode $m \in M$ where $M = \{car, train, plane\}$.

The HSR-network operator is interested in minimising costs for a given service undertaking. The main cost components pertain to the (1) '*operational*' and (2) '*maintenance*' expenses, expressed in cost per seat-kilometre. The operator is not only interested in minimising its expenses but also in maximising its revenues to maximise its net profit. Note, however, that since ticket fees constitute an expense for users and a revenue for the operator, the effects thereof are cancelled-out in the objective function expressed in Eq. (1) and are, therefore, omitted from both users' generalised travel cost as well as from the operator's cost function. The operator's cost function is stated in Eq. (3), where w_l is the (one-direction) distance of line l measured in kilometres based on the line configuration, f_l is the

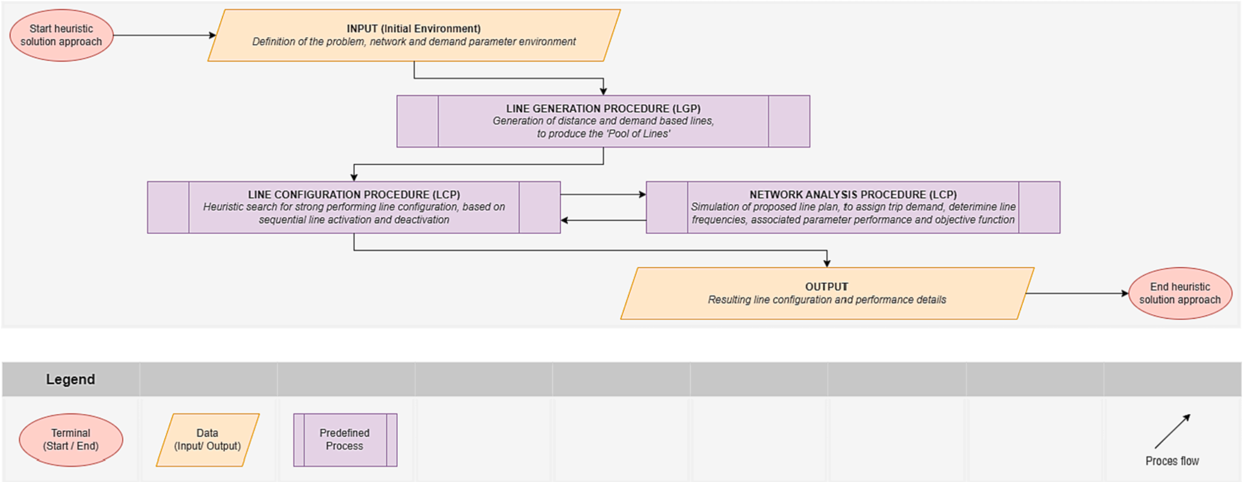

Fig. 1. High-level description of the service design and frequency setting approach.

frequency of line l, and κ is the seating capacity per HSR-train. γ^1 and γ^2 are the operational and maintenance costs per kilometre.

$$C^{operator} = \sum_{l \in L} (2 \cdot w_l \cdot f_l \cdot \kappa) \cdot \gamma^1 + \sum_{l \in L} (2 \cdot w_l \cdot f_l \cdot \kappa) \cdot \gamma^2 \tag{3}$$

$$w_l = \sum_{e \in l} w_e$$

The societal costs pertain to the effects that the user neither pays nor the operator but are imposed on society, also known as externalities. We explicitly account for the externalities generated and approximate those as a function of mode-specific passenger flows with a mode-specific external cost (which is monetised) per passenger-kilometre, γ^3_m, as follows:

$$C^{society} = \sum_m \sum_e \left[q_{e,m} \cdot w_e \cdot \gamma^3_m \right] \tag{4}$$

The objective is constrained in several manners to obtain feasible results and restrict the solution space (and thereby the computational burden). The constraints included can be divided into three categories: *'Line Design', 'Line Frequency'* and *'Passenger path'*. We briefly list them below, along with the rationale for their inclusion:

- Line design constraints: '*minimum line length*' and '*minimum number of stops*' (prevent nesting with conventional rail and assure a cross-network function); the '*round trip time*' (all trains should be able to ride back and forth within a user-specified time window); '*line symmetry*' (lines should be identical in both directions); '*infrastructural and geographical detour*' (prevent excessive detours and reduce computation time).
- Line frequency constraints: '*minimum frequency*' (non-negativity and prevents ghost lines, i.e. lines without services); '*integer frequency*' (no partial trains); '*frequency symmetry*' (guarantees cyclic service by making sure that frequencies are identical in both directions).
- Passenger path constraints are restrictions on path topology; these are: *'maximum number of transfers per path'* and *'maximum detours'* (in either geographical or infrastructure distance terms) since these paths are likely to be unattractive for travellers as well as induce a high computational burden.

3.2. Solution approach

A line generation and configuration approach where a network is configured by sequentially activating and deactivating lines is chosen to be most suitable based on the discussion provided in Section 2.2. We adopt this heuristic approach because it offers a good balance between limiting the computational burden and yielding strong performance on small samples, as well as the possibility of tracing network development. The interested reader can access the heuristic code through a public repository (Grolle et al., 2023).

Fig. 1 provides a high-level schematic overview of this approach, displaying the input, the three core modules and the obtained output. The algorithm starts with the *Line Generation Procedure*, which generates a pool of feasible and strategically designed lines. These lines are then transferred to the *Line Configuration Procedure*. This procedure guides the search by means of strategically selecting multiple sets of lines. The *Network Analysis Procedure* simulates the proposed configurations and determines their performance. Subsequently, the *Line Configuration Procedure* decides which next move is most suitable, meaning the latter two are in continuous consultation.

Fig. 2 depicts the steps included in the *Line Generation Procedure (LGP)* in greater detail. As can be seen, the procedure uses five

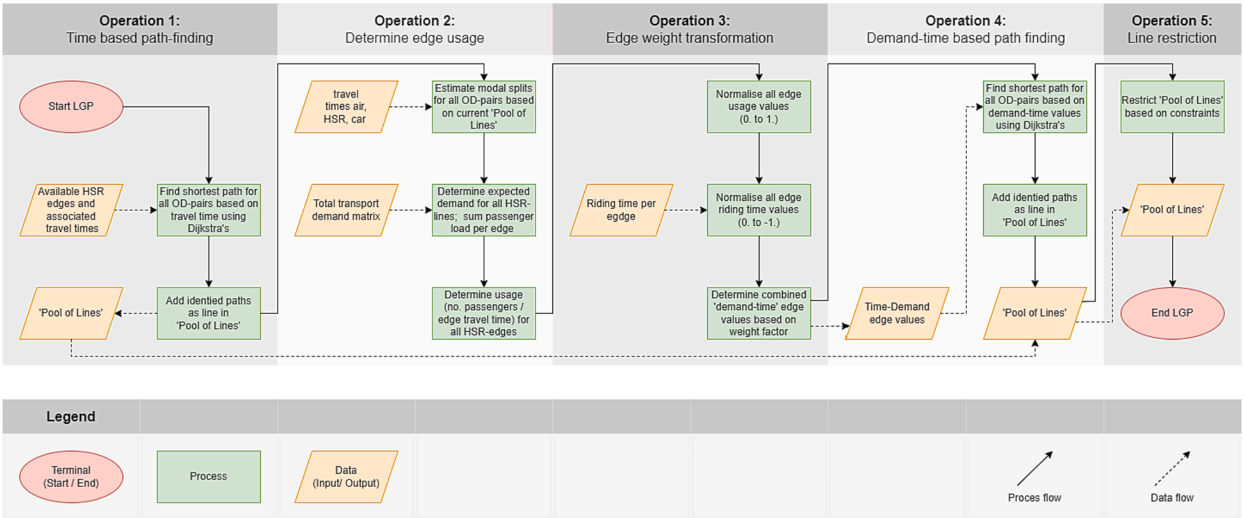

Fig. 2. Algorithmic flowchart of the line generation procedure.

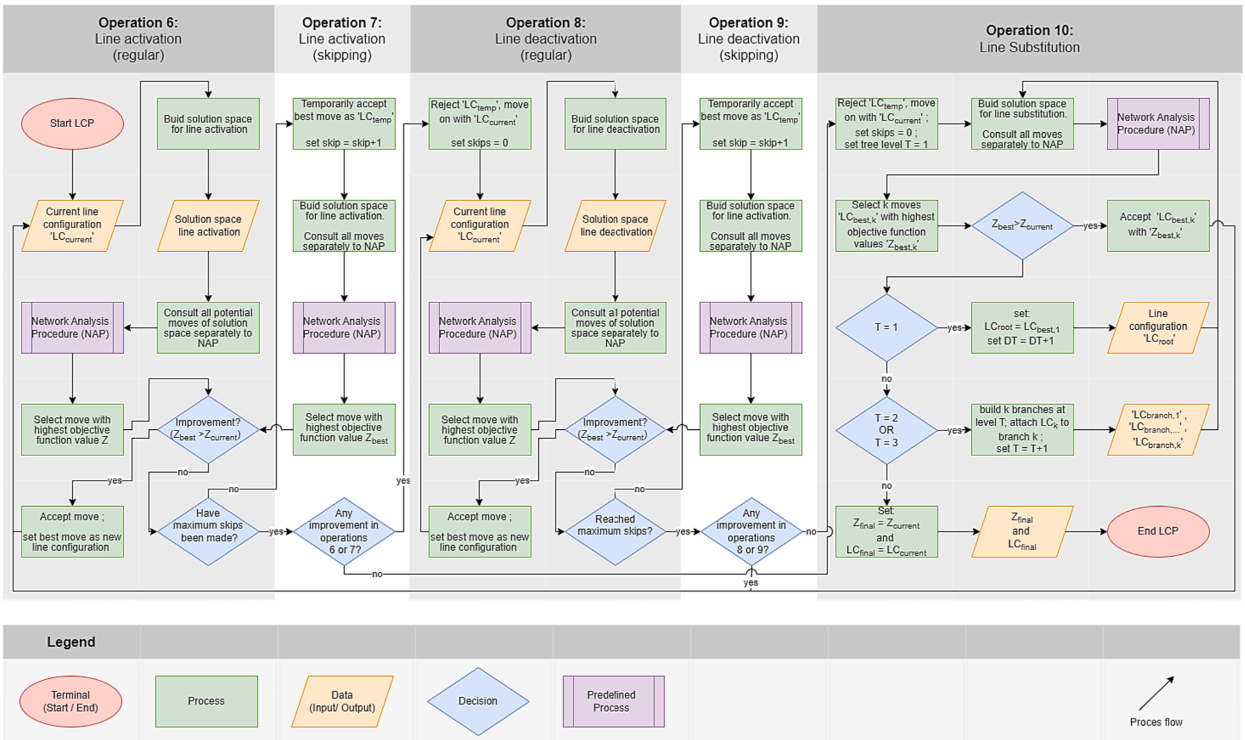

Fig. 3. Algorithmic flowchart of the line configuration procedure.

operations to work towards the construction of two line types. First, 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. In the process of generating lines, we allow for a specific detour along links for which high demand levels are expected, and 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). Finally, the set of potential lines is reduced by enforcing the line design constraints of Section 3.2, such that undesirable lines are excluded. At the end of this procedure, the remaining lines constitute the 'Pool of Lines'.

The *Line Configuration Procedure (LCP)*, as shown in Fig. 3, guides the search for attractive line configurations. We aim to strike a delicate balance between devising a lightweight approach (to allow for multiple tests) and using a small set of initial assumptions (due to limited a priori knowledge of line configurations), while maximising the likelihood of generating attractive solutions. It is therefore

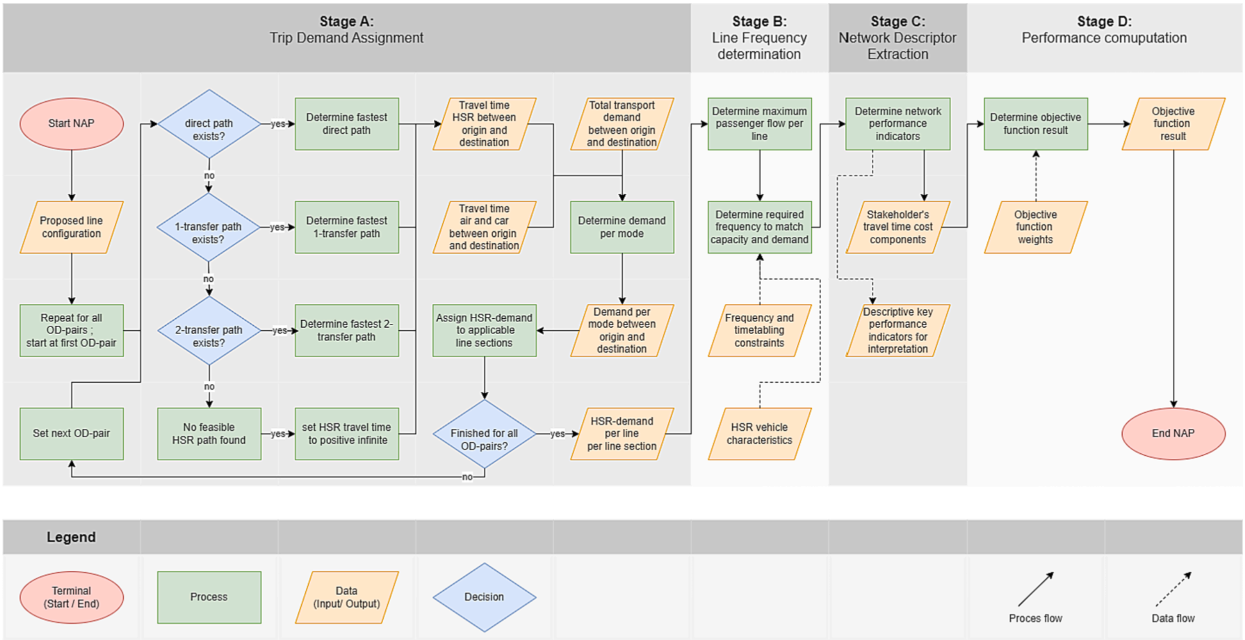

Fig. 4. Algorithmic flowchart of the network analysis procedure.

chosen to develop a customised hill-climbing heuristic approach that starts from a fully deactivated pool of lines that sequentially alternates between activating and de-activating lines. Skipping and substitution operations are included to reduce the chance of reaching local optima. Stopping criteria are selected with the goal of balancing between computational burden and solution quality.

Finally, the *Network Analysis Procedure (NAP)*, displayed in Fig. 4, starts by simulating the HSR passenger's behaviour using a lexicographic travel time and transfer minimisation strategy, similar to the approach first proposed by Han and Wilson (1982) and later adapted by Fan, 2004. Once the HSR travel options are known, the total demand is distributed over the different modalities using the Random Regret Minimisation approach proposed by Chorus et al. (2008). Following system convergence, network performance indicators are reported by the network design and line frequency setting model.

4. Application: European high-speed rail network

The problem formulation and solution approach proposed in the previous section is applied to the European HSR-context. We describe and specify the European case study and the experiments performed in the following.

4.1. *Case study description and input specification*

Our graph representation includes nodes corresponding to 124 Europe's main metropolitan areas based on population, metropolitan GDP and topographical- and rail network importance as defined by Donners (2016). These 124 nodes form the origins and destinations for all passengers within the network. In the following, we provide details on how the supply and demand of long-distance European travel are considered in our analysis. The case study data files are available through a public repository (Grolle et al., 2023).

4.1.1. *Transport supply*

Our model distinguishes amongst the prime modes of transport for long-distance travel: air, car and (high-speed) rail. The rail infrastructure between city nodes is represented based on the Trans-European Rail network vision of the European Commission (2013). Note that a part of the infrastructure is yet to be built. The access- and egress times to these stations are described as a function of a city's population, surface area and the average time required to reach its centre, assuming an average urban travel speed of 30 km/h. The in-vehicle time per link is estimated using an average cruising speed of 275 km/h (Campos & 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 min per station. Furthermore, the trains have a seating capacity of 350 seats each (Campos & de Rus, 2009).

In addition to the rail network, an air travel graph is constructed using the 384 main European airports, as defined by Eurostat (2020). The availability of a connection between any pair of airports, i.e. the existence of a link connecting two airport nodes, was also specified based on the flight registration of Eurostat (2020). The in-vehicle times on these links are estimated based on observed flight parameters: an average cruising speed of 850 km/h, with taxi & take-off and landing & taxi procedures amounting to 30 min and 50 km each. Access and egress times between cities and airports are estimated using the car travel times obtained using the API of OpenRouteService (Heidelberg Institute for Geoinformation Technology, 2020). When connecting airports and cities, the maximum acceptable access/egress time is set to 150 min. In addition, a total of 120 min of waiting time (check-in, security, etc.) is assumed.

For car travel, in-vehicle travel times and distances between all nodes are estimated using the API of OpenRouteService (Heidelberg Institute for Geoinformation Technology, 2020), which searches for the fastest route considering the European road network in 2020. We assume that an additional 10% of the non-stop long-distance travel is needed for breaks and rests.

4.1.2. Travel demand

Next, we estimate the total long-distance travel demand between the 124 previously mentioned cities. Due to the scarcity and complexity of demand forecasting models for long-distance travel, we choose to rely on observed travel data available for the airline industry in 2019 from Eurostat (2020). We then transform this data to estimate the total demand between city pairs. For this, three main challenges have to be overcome: (i) the observed flows only represent traffic between airport pairs rather than city pairs; (ii) the airports are frequently part of more complicated multi-airport-city systems, which means that their traffic cannot be assigned one-on-one to a specific city; and (iii) air traffic only represents a share of the total demand for long-distance travel and this share varies across OD-pairs, and the share thereof depends on the competition between modes.

The newly developed method consists of two stages. The first stage, called 'city pair intensity', meant to approximate a so-called city pair intensity, which corresponds to the relative distribution of air travel between city pairs. It is an auxiliary value that allows mapping travellers between airport pairs and city pairs, but which has not yet been fitted to the total demand. Subsequently, at the second stage, called 'demand fitting', we fit the acquired intensities to the observed air travellers between airports to estimate the actual traveller volumes.

Starting with the 'city pair intensity' stage, step (1) determines the city-airport systems assuming 2.5-hour catchment areas. Step (2) then follows by creating an inventory of possible air connections between city pairs considering both city-airport systems. The input for this step follows from the measured flights between the corresponding city-airport systems according to the Eurostat (2020) dataset. Next, step (3) determines at the city pair level the probability of each air connection out of the set of relevant air connections to be taken. This probability is determined using a utility maximisation approach based on flight frequencies, local access times, local egress times and the need for border crossings during access and egress. Step (4) then determines an 'average flight profile' for each city pair, which is composed of a weighted average for all travel time components, based on the previously determined expected passenger distribution amongst the set of relevant air connections. To estimate the relative significance of air transport for each city pair, step (5) estimates the modal splits using the random regret theory of Chorus et al. (2008) as applied to long-distance mobility by Donners (2016). These modal splits may be influenced by differences in the distance, the (un)availability of convenient air connections and natural barriers that hinder direct routes for car and rail. To account for this, car and rail travel is determined using the method of section 3.1. Concluding this process, step (6) combines all previous insights into a so-called intensity metric, $y_{o,i,j,d}$. This value represents a relative number of passengers that would travel by plane from airport i to airport j when travelling between origin city o and destination city d. This is calculated using a gravity model as described in Eq. (5). Here, $p_{o,i,j,d}$ and $p^{a}_{i,j}$ are the market share of a specific flight out of the available flight options connecting the respective city pair and the overall modal share of air for the same city pair. $x_{o,d}$ is the total travel demand from origin city o and destination city d. $t_{o,d}$ is the travel time of the 'average flight profile' when travelling by plane between the two cities.

$$y_{o,i,j,d} = p_{o,i,j,d} \bullet p^{a}_{i,j} \bullet x_{o,d} / (t_{o,d}) \tag{5}$$

After this, the 'Demand Fitting' part, stage B in Fig. 4, fits the previously determined intensity, $y_{x,y,i,j}$, to the observed air travel data in Eurostat (2020). Step (7) starts by summing the $y_{x,y,i,j}$ for each air connection as imposed by the city pairs using that specific air connection. Step (8) then determines for all air connections what share of travellers is induced by a given city pair, by dividing the intensity of a city pair on a specific air connection over the total intensity on that air connection. In step (9), these numbers are transformed into actual travellers. The observed passengers on air connections - as measured by Eurostat (2020) - are assigned to city pairs using the intensity shares determined in the previous step. Repeating this for all air connections and summing the demand per city pair results in an OD-matrix of air passengers between cities. Finally, step (10) transforms the matrix for air demand into a matrix for overall transport demand. Here, the air demand for a city pair is divided by the expected market share for the air modality as determined in step 6, with which the demand is scaled to reach 100%.

The demand estimation results in a total of 2,140,000 trips per day for the long-distance European network, i.e. continental trips with a distance of at least 200 km. Across the network, non-zero flows are observed for 5,174 out of the 7,688 possible OD-pairs. The weighted average Euclidian distance per trip is 812 km.

4.2. Experimental set-up

We perform a series of experiments to analyse the HSR networks' characteristics and performance under various policy priorities by altering objective function weights and HSR design characteristic parameters such as vehicle characteristics, passenger paths and line design aspects. Two scenarios are devised and specified based on the results of these sensitivity analyses.

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 estimate these costs for the European case, we adopt the differentiated value of travel time components following Ramjerdi et al. (2010), i.e. €50.0/h in-vehicle, €67.5/h access/egress and €75/h waiting and transfer. The HSR operator's operation and maintenance costs are approximated at €0.130 and €0.0122 per seat-km, respectively (Campos & de Rus, 2009). Furthermore, seven main externalities for long-distance transport are considered: '*accidents*', '*air pollution*',

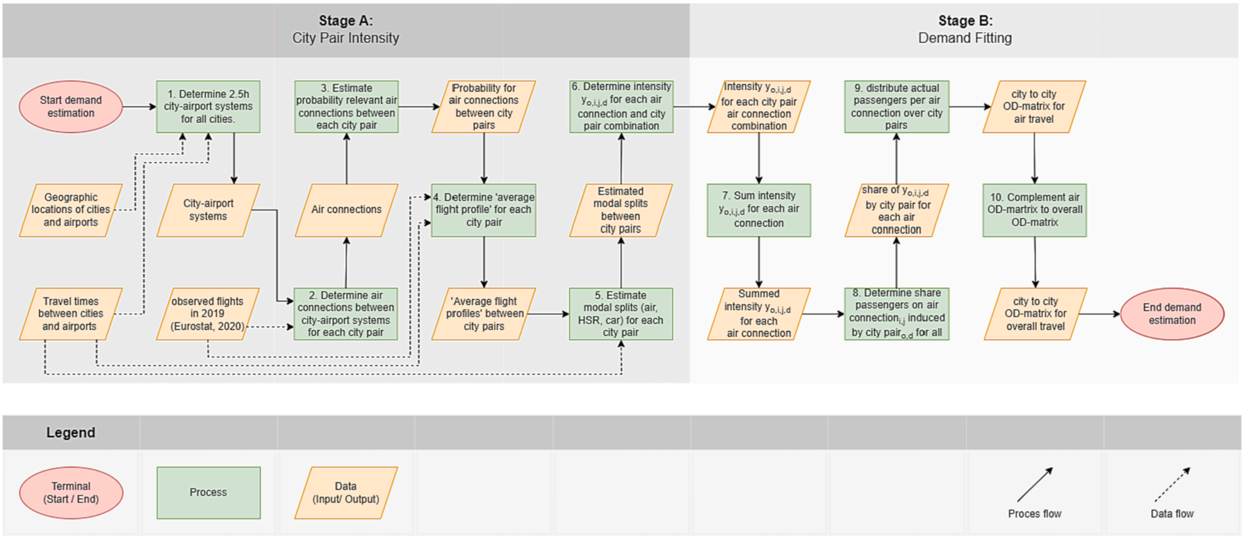

Fig. 5. Algorithmic flowchart of the demand estimation methodology.

'*climate*', '*noise*', '*congestion*', '*well-to-tank*' and '*habitat damage*' (CE Delft, 2019). The negative external costs are expressed in price per passenger-kilometre. The three alternative travel modes total in €-cent/pass-km values of 4.3 for air, 1.3 for HSR and 12.1 for car (CE Delft, 2019). In addition, we use the following specifications for the line configuration rules: the minimum line length was set to 200 km, the minimum number of stops at three, the round-trip time to 18 h and the minimum frequency to one, i.e. allowing for daily trains.

The first scenario, denominated '*Economic*', aims for a high cost-efficiency with an equal distribution of objective function weights for all stakeholders, i.e. $\Psi^{user} = \Psi^{operator} = \Psi^{society} = 33.3\%$. The second scenario, denominated '*Extensive*', is geared more towards minimising user's costs and maximising societal objectives, as reflected by the following weight distribution: $\Psi^{user} = 37.5\%, \Psi^{operator} = 25\%, \Psi^{society} = 37.5\%$. The results of these two scenarios are compared to a baseline scenario where societal costs are neglected ($\Psi^{user} = \Psi^{operator} = 50\%, \Psi^{society} = 0\%$). The *Economic* scenario will likely offer more value for money, whereas the *Extensive* scenario will yield greater contributions towards policy goals. Below, the outcomes of the two scenarios are compared with each other and those of the baseline case. In addition, for completeness, we report in the appendices the results of a large set of sensitivity analyses in relation to policy priorities and government strategies (Appendix A) and HSR design variables (Appendix B).

The model is implemented in '*Python 2.7.16*' using '*Spyder 3.3.6*'. All tests are performed using a PC with Intel® processor, Core™ i5-8500, 3.00 GHz and 16 GB RAM memory. To limit the computational burden, only the 985 OD-pairs with a minimum daily demand of 40 passengers - accounting for 90% of the overall travel demand - are considered in the following analyses. To assess the performance of the new heuristic, it was first tested on a smaller problem instance (Germany: 17 cities, 18 possible lines). The exhaustive search required 10,486 s (~3 h), whereas the heuristic managed to reach the global optimum solution in 379 s (<6.5 min). Expanding to the European network with 124 cities, the heuristic required 2–3 days on average to reach its final solution.

5. Results

The baseline scenario (where societal costs are neglected) results in an HSR-network connecting 89 cities. The final network yields a positive net present value (NPV) of €24.9 million per day and an HSR modal share of 14.7%. The solution process experienced difficulties connecting subnetworks, which is confirmed by the low share of transferring passengers (only 7.5% of HSR passengers performing a transfer). This baseline scenario should be considered a lower bound for network extensiveness (e.g., reachable OD's), subsequent usage (e.g., HSR modal share) and resulting benefits (reduction of stakeholder costs) for later comparisons.

The simulation of the baseline and improved networks led to observing multiple recurring and differing patterns. In the following, we present the main recurring design patterns observed for the resulting networks under alternative scenarios (5.1), followed by the analysis and comparison of their differences in design and performance (5.2).

5.1. Network design patterns

The non-baseline scenarios – Economic and Extensive - resulted in functional continent-wide networks. In the following, we present the results of the latter for illustration, whereas in the next section, we provide a comparison of both of which against the baseline scenario. A visualisation of the resulting line configuration for the *Extensive* scenario is presented in Fig. 5, with the colours depicting individual services and the width associated frequencies. The names of selected cities are presented for orientation.

The map provides an indication of the scale and form of the network, as well as its focal points, which are overall comparable for all

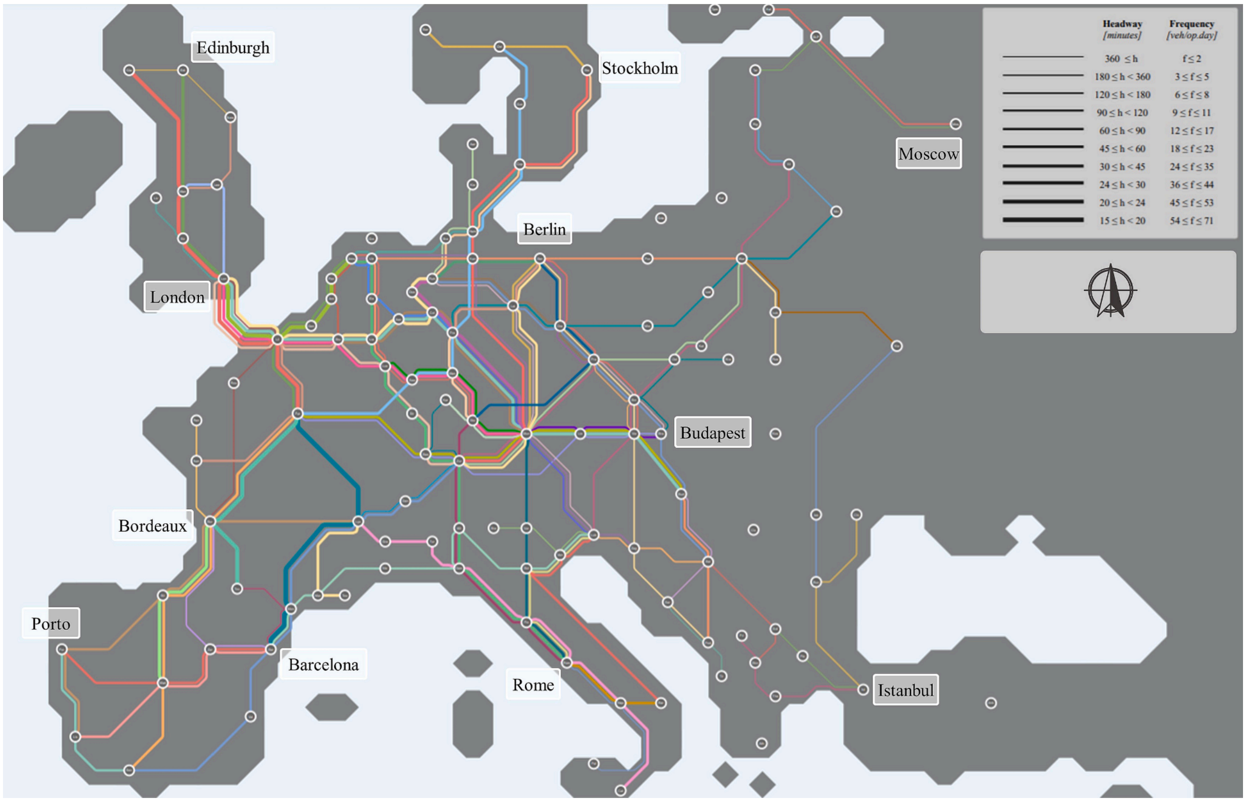

Fig. 6. Transit map of the HSR-services in the 'Extensive' scenario.

scenarios. Most notable is that the majority of lines are visiting multiple countries. This highlights the importance of interoperability and cross-border cooperation, as the underlying travel demand patterns justify these. We observe commonly prevailing patterns both in terms of the global network characteristics as well as in terms of the configuration of the sets of lines included, as discussed in the following.

All model runs result in lines running across the continent, as well as exhibit similar patterns in terms of selected and unselected cities or regions. Certain areas are not selected because of their lower demand or unfavourable geographical characteristics. We make the following three observations in relation to global network characteristics: (1) *Network density* increases towards the geographical centre of the case study area, in this case, Germany. In particular, Munich consistently emerges as a primary hub, followed by other key German cities and more (geographically) peripheral focal points like London, Lille, Bordeaux, Bologna, Copenhagen, Zurich, Warsaw, Budapest and Bucharest. This indicates that hubs are not necessarily the largest cities but rather those strategically located; (2) *Network extensiveness and density* are slightly skewed towards the western part of the case study area because of the more intense demand flows amongst Western European cities compared to their Eastern European counterparts, and (3) *Cities that are frequently left unserved* in the obtained solutions are characterised by lower demand and are not located between at least two higher demand cities (examples of which include Rouen, Toulon, Groningen and Gdańsk).

We also make the following observations in regard to line configuration. Four recurring line types are observed. All networks feature 5–20 (depending on the extensiveness) relatively long lines (length > 1000 km; number of stops > 6) that can sustain frequent, hourly services (~18 trains/direction/day). These lines are selected during an early phase of network development. These lines follow routes with relatively high and stable demands along the visited nodes, such that they benefit from joint corridor effects, which consist of several lines merging and splitting along the corridor. An example of this is the route between Amsterdam and Rome.

The remainder, and also the majority, of lines have a shorter profile (length < 1000 km), which can be further subdivided into three categories (1) Lines that strategically connect to corridors, like the Rennes-Nantes-Bordeaux line, such that new cities are linked to the network. A decision which is justified by the total demand related to these newly introduced cities; (2) lines that produce sufficient demand by themselves, such as the Bergen-Stockholm line, which means that they are found in both low and high-density areas, and (3) additional lines, which primarily follow one or a few legs of a main corridor, to allow offering a larger allocation of seating capacity and thereby better catering for demand variations along established corridors. Bordeaux-Madrid is an excellent example of this.

Next, we investigate the HSR-network utilisation. Fig. 6 presents the daily vehicle loads per link in trains per direction per day for the solution obtained in the *Extensive* scenario. Striking observations are: (1) the high link loads (purple links) are located in proximity to geographical bottlenecks (Iberian Peninsula, Great Britain, Scandinavia); (2) the relatively high HSR flows (blue links) connect to middle-size intermediate cities (Bordeaux, Edinburgh, Glasgow, Bari and Lyon), which can be explained by the more locally-oriented

Table 1
Descriptive characteristics of the developed service networks.

	Unit	Baseline	Economic	Extensive
Number of lines	[-]	54	83	91
Connected cities	[-]	89	110	116
Reachable ODs	[-]	396	944	1148
Average line length	[km]	738	834	831
Avg. stops per line	[no. cities]	4.0	4.6	4.7
Avg. frequency per line	[trains/day]	9.2	9.1	11.0
Available-seat-km	[10^6 km]	277	499	633
HSR-pass-km	[10^6 km]	168	300	378
Average 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
Average HSR trip distance	[km]	488	558	589
Share direct passengers	[%]	92.0	87.5	77.8
Share 1-transfer pass.	[%]	7.5	12.5	22.2
Share 2-transfer pass.	[%]	0.5	*n/a*	n/a

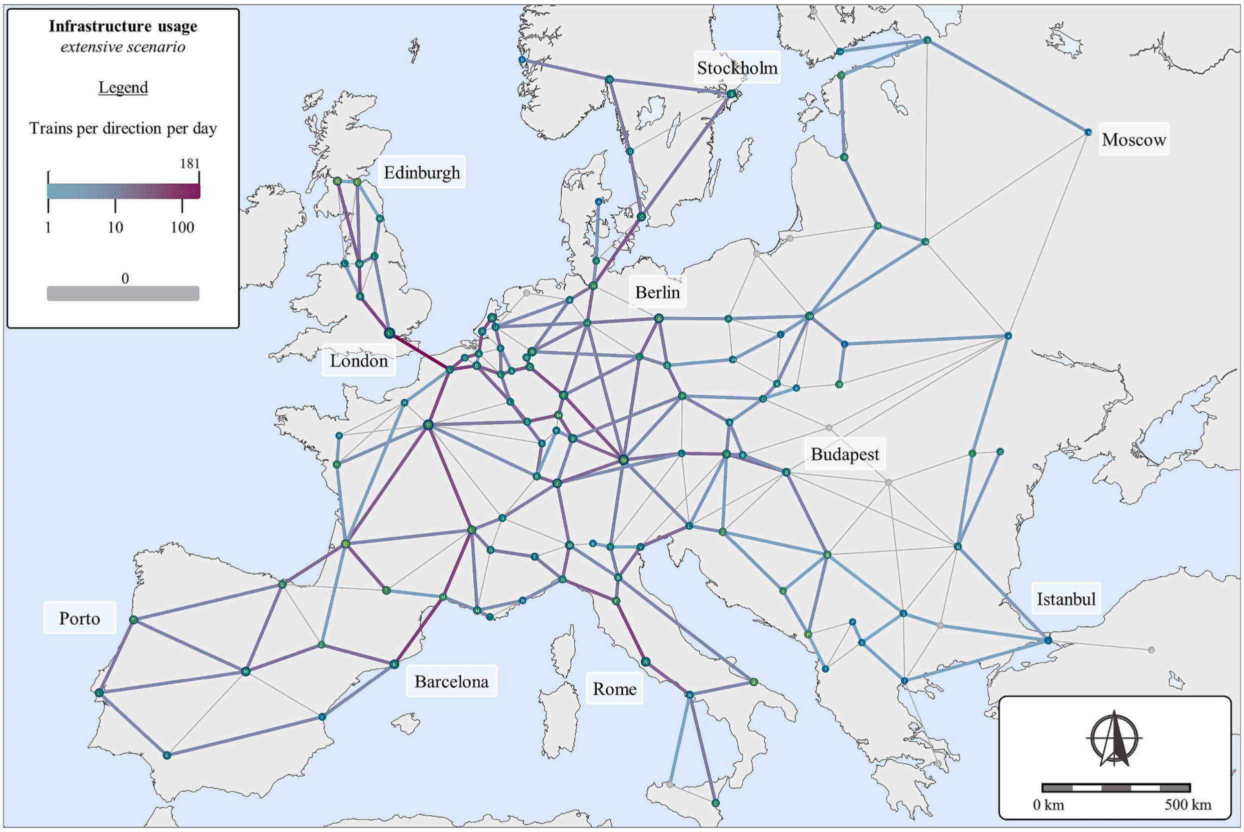

Fig. 7. Infrastructure usage (trains per direction per day) of the HSR-network in the 'Extensive' scenario.

demand patterns whilst being large enough to generate the intersection of multiple lines; and (3) the thinnest links (shown in grey), which have flows that are considerably smaller than the capacity of a single train and are thus not served. (Lublin, Tirana, Priština).

5.2. Network performance analysis

We now turn to assessing and comparing the performance of the networks obtained for the *Economic* and *Extensive scenarios,* as well as comparing those to the baseline case.

The descriptive KPIs, as shown in Table 1, show distinctive results for network development when comparing the two scenarios. This is primarily confirmed by the increased HSR-passengers-kilometres (+26%) and available seat kilometres (+27%) in the *Extensive*

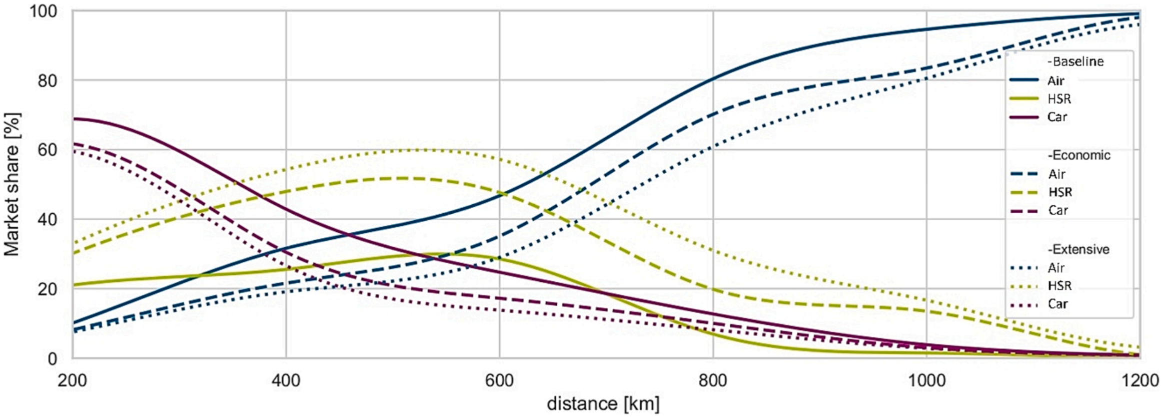

Fig. 8. Market share per travel mode as a function of travel distance.

scenario as compared to the *Economic* scenario. These differences are even more pronounced when comparing the *Extensive* scenario to the *Baseline* case (+125% HSR-passengers-kilometres and +129% available seat kilometres).

Next, we investigate the consequences for the induced modal shifts. Model results show an HSR trip modal potential of 14.7% (*Baseline*), 25.0% (*Economic*) and 29.9% (*Extensive*), respectively (Table 1). The market share as a function of travel distance is plotted in Fig. 7. The modal split is dominated by the car for relatively short trips (200–300 km) whereas market shares of 30–40% for air, HSR and car are observed for 500 km trips (see Fig. 8). After this, the air share gradually grows to a share of 90% by 1000 km. A comparison of the *Economic* and *Extensive* scenarios shows that HSR is especially more attractive under the latter for longer distances (600–1000 km), primarily at the cost of the market share of air travel. This is the outcome of the better network integration and coverage attained under the *Extensive* scenario.

Next, we turn to analysing cost aspects and stakeholder benefits. From the user's perspective, benefits are primarily yielded from time savings in waiting (fewer air travel) and in-vehicle (fewer road travel) durations. Both factors significantly outweigh the newly introduced transfer times and increased access/egress times, especially for longer HSR trips. The reduced external costs are mainly driven by the shift from car traffic (72%) as opposed to air traffic (28%). This makes that for the societal (external) costs, the most substantial benefits of substitution towards HSR pertain to accidents, congestion and climate. Furthermore, results show that for a developed HSR-network, only 31% of societal benefits can be explained by environmental factors of air pollution, climate, habitat damage and noise, with the remaining (69%) stemming from congestion reduction and safety benefits. As could be expected, aiming for policy goals (mobility, social cohesion or sustainability) rather than cost-efficiency, the *Extensive* scenario provides a less beneficial cost-benefit ratio than the *Economic* scenario does.

Finally, we would like to reflect on model validation aspects. A meaningful comparison or validation of our demand estimation and model results on a European level is unfortunately hindered by the lack of detailed and reliable figures for long-distance travel in the EU, which is due to various limitations on data collection (e.g. the absence of a single ticket identification system) and availability due to protective commercial interests (European Commission, 2021). A comparison with findings reported by past studies confirms that our model results in terms of modal split distribution per distance category (see Fig. 7) are in line with those reported by mode choice studies for long-distance travel in Europe, such as Goeverden and van Arem (2010) and Albalate et al. (2015). In addition, the number of passenger air trips per day obtained by our modal split (see table) is well aligned with the figures reported by Eurostat (2022). While these face-validity checks offer some confidence in our model, more detailed disaggregate demand data will be needed to validate our demand estimation and distribution modules.

6. Conclusion and discussion

We developed a customised version of the '*Transit Network Design and Frequency Setting Problem*' (TNDFSP) for the long-distance transport context and high-speed rail in particular. We then also designed a heuristic solution strategy consisting of three modules: *Line Generation Procedure*, *Line Configuration Procedure* and *Network Analysis Procedure*. The former is performed as an initialisation phase, whereas the latter two are solved iteratively. We apply the proposed method to study the users', operator's and societal performance of a European high-speed rail network by conducting an extensive series of experiments and sensitivity analysis to test for the network's performance under various policy priorities and design variables.

The network designs obtained by our method feature certain common features. They consist of a set of longer (1000–2000 km) and high frequency (~18 trains per direction per day) lines, which form a series of main corridors, often connecting multiple countries. These findings highlight the importance of cross-border cooperation and rail interoperability. This calls for policy making to adopt a continental perspective which goes beyond national borders by identifying and investing first in few selected high-demand and high-capacity corridors rather than hope that a patchwork of specific cross-border connections will eventually merge to form a network at a continental scale. Furthermore, not all selected cities and countries were connected by our model, as these are not justified from a network perspective. Both arguments plead for an overarching design view as in the absence of which - as history and the current state

Table A1
Relative effects of policy priorities and governance strategies on selected KPIs, indexed (1 0 0) at '3. Total Welfare (CO)' scenario for comparison.

		1 Liberalisation	2 Total Welfare	3 Total Welfare	4 Mobility	5 Sustainability	6 Future Proof
Weight (ψ): User		50%	33%	33%	50%	25%	38%
Weight (ψ): Operator		50%	33%	33%	25%	25%	25%
Weight (ψ): Society		0%	33%	33%	25%	50%	38%
	unit	**Free market**		**Centralised organisation**			
		Operator costs reduced by 20%		*Transfer time reduced by 50%*			
Number of lines	[-]	96	100	100	123	130	143
Connected cities	[-]	93	100	100	105	107	109
Reachable ODs	[-]	76	119	100	165	173	169
Total Benefits	[-]	92	113	100	92	97	97
User Benefits	[-]	90	97	100	114	115	117
Operator Benefits	[-]	118	119	100	70	70	70
Societal Benefits	[-]	84	101	100	127	134	129
Available seat km	[-]	85	105	100	143	143	143
Average load factor	[-]	97	97	100	95	102	97
Average line length	[-]	105	108	100	109	99	106
Avg. no. of stops per line	[-]	100	103	100	108	103	110
Avg. frequency per line	[-]	86	92	100	102	107	92
Avg. HSR trip distance	[-]	97	101	100	108	110	108
HSR-pass-km	[-]	82	102	100	136	145	138

of the European rail network make clearly evident - national and company interests result in a patchwork of poorly connected subnetworks.

Our analysis suggests that service designs yielded by the consideration of externalities result in more extensive networks with larger coverage and modal shift, which would indeed reduce negative externalities in long-distance travel. For such a network to materialise, high public investments are needed. If realised, the estimated modal share of HSR in the long-distance transport context (>200 km) is then expected to roughly double compared to the baseline level of roughly 15% to 25–30% at the cost of both air travel (down from 62% to 53–57%) and car (down from 23% to 17–19%). For policy makers to make strategic decisions on such large-scale investments, there is a need for more advanced models of long-distance travel demand and of the long-distance travel market.

Inevitably, simplifications and assumptions were made in our modelling and experiments. In this study, we assumed the complete availability of high-quality and interoperable high-speed rail infrastructure throughout the network. This enabled us to establish an upper-performance limit and prevents a tunnel vision if we were to strictly restrict our analysis to the limited set of already existing possibilities. Throughout our analysis, however, we made sure to make conservative estimates. Future research may relax some of the assumptions made in relation to both travel demand and the related market. For the former, one may estimate potential demand generation resulting from improved accessibility and connectivity based on empirical knowledge from past implementations of HSR. Givoni and Dobruszkes (2013) estimated induced demand to amount to 10–20% in their review. It is however unclear whether such an increase will apply also when extending the network beyond the highest-demand corridors. Similarly, other demand-side effects such as the impacts of accessibility on traveller destination choices can potentially enhance demand estimations (e.g. Birolini et al., 2020). Findings from stated and revealed preferences studies on the determinants of long-distance travel can enrich the mode choice model to include an array of individual- and alternative-related attributes such as comfort and reliability for business and leisure travel. Furthermore, attitudinal studies may shed light on the main barriers for inter-modal long-distance travel and offer directions for furthering air-rail service integration.

Next to obtaining better estimate of travel behaviour and its implications for demand forecasting under different scenarios, several key aspects of the long-distance travel market call for special attention by both policy makers and researchers: (i) cross-mode competition – the impact of HSR introduction on air travel supply (for related evidence see Dobruszkes et al., 2014); (ii) cross-mode collaboration – the impact of integrated air-HSR services (Zhang et al., 2018); (iii) competition amongst service providers – the role of dynamic pricing and revenue management, and; (iv) traffic market – the track and platform allocation of HSR services in relation to other train services. Future work should devote efforts to understanding the underlying market dynamics so as to potentially forecast market evolution in response to alternative scenarios as well as identify both supply- and demand-management measures, such as short-haul flight bans and tradable mobility credits, respectively, to stimulate developments in line with policy objectives.

We hope that the results of this research will contribute to the ongoing public and professional debates on designing an attractive and competitive European HSR-network. While this research field is yet relatively in its infancy, our findings underscore that in weighing different policy options, the design of a mature European HSR-network should be included amongst the options to be considered.

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Table A2
Effects of policy priorities and governance strategies on selected KPIs.

		1 Liberalisation	2 Total Welfare	3 Total Welfare	4 Mobility	5 Sustainability	6 Future Proof
Weight (ψ): User		50%	33%	33%	50%	25%	38%
Weight (ψ): Operator		50%	33%	33%	25%	25%	25%
Weight (ψ): Society		0%	33%	33%	25%	50%	38%
	Unit	**Free market**		**Centralised organisation**			
		Operator costs reduced by 20%		*Transfer time reduced by 50%*			
Modal share air	[%]	62.1	60.6	60.7	58.1	57.3	57.7
Modal share HSR	[%]	14.7	17.5	17.3	21.7	22.2	22.1
Modal share car	[%]	23.2	21.0	22.0	20.3	20.0	20.2
Direct pass.	[%]	92.0	86.3	83.7	76.9	72.0	79.8
1-transfer pass.	[%]	7.5	12.9	15.5	19.9	25.1	18.3
2-transfer pass.	[%]	0.5	0.8	1.9	3.2	2.9	1.9

CRediT authorship contribution statement

Jorik Grolle: Writing – original draft, Conceptualization, Methodology, Software, Visualization. **Barth Donners:** Supervision, Conceptualization, Validation, Formal analysis, Resources, Writing – review & editing. **Jan Anne Annema:** Supervision, Conceptualization, Validation, Writing – review & editing. **Mark Duinkerken:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing. **Oded Cats:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing, Project administration.

Declaration of Competing Interest

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

Data availability

Available via a public repository (referred to in the paper): https://data.4tu.nl/datasets/ea9f1238-0cc8-47ba-b8c6-3e0846fb8d19

Appendix A: Sensitivity analysis towards policy priorities and governance strategies

A sensitivity analysis consisting of six diverging scenarios is performed to test the effect of different policy priorities and governance strategies. Table A.1 and Table A.2 present the outcomes of our experiments. Table A.1 presents normalised results for the attributes in different scenarios when indexed to scenario '3 Total Welfare', allowing for direct comparison. Table A.2 reports the actual values of attributes described in percentage terms. The two main governance strategies are defined as '*free market*' (scenarios 1–2), which benefit from competition and subsequent cost-efficiencies (modelled as a 20% reduction in operator costs), that can be contrasted with the '*centralised organisation*' (scenarios 3–6), which benefits from better network integration (modelled as a 50% reduction in transfer times). Different priority scenarios are tested by adjusting the weights (ψ) of the objective function (equation (1). These weights are varied from the non-consideration of externalities (scenario 1), equal weights to all three perspectives (scenarios 2, 3), and variations of importance attached to the different perspectives (scenarios 4, 5, 6, see details in Table A.1 and Table A.2).

Governance: Isolating the divergent characteristics of governance strategies (scenarios 2 & 3) suggests a stronger cost-efficiency of a free market solution (total benefits) whilst offering relatively similar extensiveness (HSR-passenger-kilometres (HSR-pass-km), number of lines, number of connected cities) and performance (user and societal benefits), when compared to the centrally organised network. The benefits of the free market scenario mainly stem from the assumed substantial reduction in operator costs.

Policy priorities: The consideration of external costs induces a strong growth in the extensiveness (available-seat-kilometres; ASK), usage (HSR-passenger-kilometres, number of transferring passengers) and the network's performance. However, mixed results are found for the differences in costs and benefits. A more extensive network is obtained under free market conditions. This extended network is associated with key performance indicators that reflect a more mature design (more transferring passengers, higher load factors), as well as a better net profit value (NPV). The centrally organised scenarios lead to lines that are not necessarily the most cost-efficient but that do contribute to societal goals (sustainability, mobility, or social cohesion) in the form of reduced user costs (travel time) and societal costs (externalities) and result with an improved net-profit-value.

Appendix B: Sensitivity analysis towards high speed rail design variables

To assess the effect of various design variables, a sensitivity analysis on ten design parameters is performed. The results are summarised in Table B.1. The studied parameters are listed on the vertical axis, whereas the effects on key performance indicators related to goals are shown on the horizontal axis. The values are the average expected change of the indicator given the defined interval of the design variable. An exemption applies to values that reached peak value (optimum), indicated with an asterisk, where these

Table B1
Relations between HSR design variables and KPI contribution to policy goals.

							Operator (cost-efficiency)				User (mobility)			User (soc. cohesion)			Society (sustainability)		
						KPI	Total costs savings	Operator costs	Avg. load factor	Share transfer pax	User costs savings	APK HSR	Share direct pax	No. connected cities	Reachable OD's	No. of lines	Societal costs savings	pass-km HSR	Modal split HSR
						Base value	€2 – 2.5 *10ˆ7	€2 – 3.5 *10ˆ7	60 – 65%	10 – 20%	€3 – 4 *10ˆ7	275 – 635 *10ˆ6 km	80 – 90%	90 – 115 (of 124)	400 – 1150 (of 1300)	50 – 90	€1 – 1.5 *10ˆ6 km	175 – 375 *10ˆ6 km	15 – 30%
	parameter	**unit**	**range**	**interval**	**peak**		**Relation factor**												
vehicle	Cruising speed	[km/h]	225–375	50	n/a	**Relation factor**	+28%	+15%	+0%	+21%	+24%	+15%	−5%	*var.*	+7%	+2%	+9%	+15%	+10%
	Seating Capacity	[seats]	350–600	50	n/a		−1%	−4%	−1%	−5%	−2%	−4%	+1%	−2%	−6%	−5%	−4%	−4%	−3%
Passenger path	Max. no. of transfers	[trf.]	0–2	1	*1		* −3%	+9%	*-6%	*var.*	* −3%	+9%	var.	−1%	+23%	*-6%	* −10%	* −11%	*+9%
	Avg. transfer time	[min]	15–60	15	*30		−2%	−8%	−0%	−28%	−6%	−8%	+7%	*-5%	−9%	+2%	−7%	−9%	−7%
	Geo. detour excl.	[-]	1.05–1.25	0.05	n/a		+11%	+11%	+1%	*var.*	+11%	+11%	*var.*	*var.*	+16%	*var.*	+10%	+12%	+11%
	Infra. detour excl.	[-]	1.05–1.25	0.05	n/a		−3%	+3%	+0%	+7%	*var.*	+3%	−2%	*var.*	+6%	+2%	+2%	+3%	+2%
Line Design	Min. no. of stops	[stops]	2–6	1	*3		* −8%	var.	* −5%	−11%	* −4%	*var.*	+3%	*var.*	*var.*	* −8%	* −2%	*var.*	*-3%
	Usage detour factor	[-]	0–1	0.125	*0.125		−1%	* −2%	−0%	+2%	* −1%	* −4%	−0%	*var.*	−2%	−2%	* −2%	* −2%	* −2%
	Geo. detour constraint	[-]	1.25–1.75	0.25	n/a		+1%	+2%	+1%	−16%	+1%	+2%	+4%	+5%	+5%	+15%	+1%	+2%	+2%
	Infra. Detour constraint	[-]	1.25–1.75	0.25	*1.50		*-2%	*-1%	+0%	−2%	* −2%	* −1%	+1%	* −2%	* −1%	+5%	* −2%	* −1%	*-1%

- Explanation: Base value is expected to change with the relation factor when parameter is increased with the interval within the range boundaries.
- Special case – peak*: Base value reaches the top at peak and changes with same relation factor in both directions from that point.
- Special case - var.: no clear pattern could be identified.

changes work in both directions. Below, the vehicle, passenger path and line features are discussed. The last paragraph includes an example with an extract from the table.

Vehicle Characteristics: Increasing the cruising speed allows for a higher level of HSR service and thereby contributes to all policy goals (i.e., positive changes reported in Table B.1). A higher seating capacity makes it harder for the operator to accurately assign capacity, resulting in 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.

Passenger path features: The relevance of passenger path constraints for the obtained solutions is demonstrated by the development of a disconnected graph consisting of several non-connected 'islands' in unrestricted cases. Especially the geographical detour exclusion is found to substantially impact the obtained results.

Line design: The lower rows in Table A.2 present the adjustments in the lines that compose the '*Pool of Lines*'. The most critical observation regards the usage detour factor. This factor controls the degree to which lines are allowed to deviate from their shortest distance-based routes to paths that have a higher expected demand. This ensures that lines are less likely to skip important nodes because a slightly shorter route is possible. Including these demand-based lines is beneficial to most user and societal goals, although it also comes at the cost of operator efficiency. The table shows that this factor peaks at 0.125, meaning that this factor is to be balanced for optimal performance. Increasing or decreasing this with one interval step (0.125) changes each indicator with its respective relation factor. For other non-peaking indicators, the base value changes with the given relation factor when using a positive interval step and changes in the opposite direction and with the same magnitude when applying a negative step.

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