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The Effects of the Planned High-Speed Rail System on Travel Times and Spatial Development in the European Alps

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One of the direct effects of introducing high-speed railway lines is a significant reduction in travel times between major cities. This is particularly relevant in mountain areas. It not only makes cities more easily reachable with more sustainable transport systems but can also encourage different travel behavior and reduce environmental pressures on sensitive areas. A comprehensive analysis of the spatiotemporal effects of the introduction of high-speed railways in the Alpine arc has not yet been developed. To help fill this gap, this study uses multidimensional scaling and the geographical information system to illustrate the time–space compression. This term indicates the erosion of spatial and temporal distances in the areas of the Alps directly affected by the new railway lines. Six trans-Alpine high-speed railway lines are analyzed, comparing current and projected travel times by train. A time-based map is created to show the time–space compression in every transversal direction, particularly on the French and the Austrian side of the Alps. Implications in terms of local accessibility are also analyzed, focusing on the Autonomous Province of Bolzano/Bozen-South Tyrol. Finally, the paper discusses the importance of time-based maps for the understanding of sociospatial dynamics and the possible implications for spatial development.

Keywords: *High-speed railway; time-scaled mapping; multidimensional scaling; GIS; accessibility; Alps; Europe.*

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Introduction

To reach ambitious European environmental targets (EC 2014), EU transport policy emphasizes the importance of a more balanced development of transport modes (EC 2011). This should limit the development of air transport and the resulting saturation of the skies, seen as one of the main causes of transport unsustainability (Regan 2014). Among the terrestrial transport modes, roads and private vehicles currently have the major traffic share. However, the increasing volume of road traffic is not sustainable, causing high levels of congestion and local and global pollution (Black 2010), especially carbon dioxide (CO_2). The introduction of alternative fuels (Nocera and Cavallaro 2016a) can only partially reduce these problems; some integrative measures that encourage the shift from road to other transport modes are required as well. Transport planning plays a key role in these matters (Sinha and Labi 2007; Nocera and Cavallaro 2014): the development of alternative transport systems such as rail is a key measure to encourage less use of private transportation and reduce air pollution (Van Essen et al 2003; Nocera et al 2015).

The European Union is fostering the construction of the Trans-European Transport Network (TEN-T; EC 2003), an integrated system of different transport modes in which high-speed railway (HSR) lines play a major role. The basic hypothesis is that HSR will considerably reduce travel times, leading to a shrinking of space and to relevant effects on travel behavior, the regional economy, accessibility, and society. Benefits are expected in marginal areas and particularly in mountain ones. In mountains the topography and technical characteristics of historical railway lines lead to high travel times and limited accessibility—2 issues that limit the competitiveness of transport by train (Nordregio 2004).

This paper uses visual methods to project the changes in travel times that are expected to be caused by the introduction of HSR within the Alpine arc. To represent the variations between current and projected (post-HSR completion) travel times and the new relationship between space and time in the Alps, we constructed a time-scaled map. Instead of displaying spatial distances, this map visualizes time distances between locations. Similar work on the impact of HSR at European level was published by Spiekermann and Wegener (1994); the

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analysis by Axhausen et al (2008) was accurate and methodologically robust but limited to Switzerland. No contribution has been developed yet for Alpine areas. This paper illustrates the time–space compression expected to occur for the major stations along the new Alpine HSR and discusses the implications of these results for local accessibility in mountain territories. The aim is to provide useful information to support spatial and transport planning, as well as policy-making.

Theoretical framework

Accessibility

Accessibility plays an important role in transport planning (Dühr et al 2010); it can be defined as the costs, within a specific region, of overcoming spatial distances (Kramar 2007). One such cost is travel time, which includes time spent in a vehicle and out of it—for example, waiting and moving to and from the vehicle (Sinha and Labi 2007). This paper focuses on in-vehicle travel time.

The effect of HSR on accessibility is important but not easy to determine. On the one hand, it reduces travel times between cities on HSR lines; on the other hand, it can cause a reduction of services on the secondary routes and increase differences between sites with an HSR station and other nearby places. This effect, known as the "tunnel effect" (Plassard 1991), may lead to unbalanced development and exacerbate the marginalization of some peripheral, including mountain areas (EC 1999).

Time-based maps

Distance-scaled maps as symbolic representations of spatial relations between objects are commonly used to visualize aspects of accessibility. Usually they indicate the physical distance between locations without showing the time needed to travel between them. However, travel time can also be incorporated into the process of map production.

Travel-time maps have a long history. Common forms include isochrones maps, which display areas of equal travel time between selected points on a map by preserving the spatial distances between points (Galton 1881; O'Sullivan et al 2010), and time-scaled maps, in which points on a map are organized in a way that the distances between them are based on travel times and not on physical distances. Time-scaled maps have two properties: (1) short travel times between two points are represented close together on the map, whereas points separated by long travel times appear distant; (2) the scale is no longer in spatial units but in temporal units, which results in a distortion of the map compared to the physical maps (Spiekermann and Wegener 1994). Time-scaled maps were introduced in the 1960s (Tobler 1961; Bunge 1962) and refined in the 1970s using algorithms (Forer 1974; Clark 1977; Shimizu and Imoue 2009). These included the multidimensional scaling algorithm (MDS; Marchand 1973; Ewing 1974), which is a set of transformation techniques that rescales physical points on maps into time-scaled points, as will be explained in detail below.

Study area

This study focused on the portion of the Alpine arc where the 6 trans-Alpine HSR lines are under construction: Genoa–Marseille, Milan–Lyon, Genoa–Basel, Genoa–Zurich, Verona–Munich, and Venice–Vienna (Figure 1). We considered the time required to travel a complete route with the fastest existing trains (in France, Train à grande vitesse; in Switzerland, EuroCity; in Germany and Austria, InterCity Express; in Italy, Frecciarossa), not including wait times. The routes can be described as follows:

- The Genoa–Marseille line connects the Liguria and Côte d'Azur regions. It was built as a single track during the 19th century, and the renovation of the existing line continued slowly throughout the 20th century. Despite its importance, part of the Italian stretch between Genoa and Ventimiglia remains a single track due to technical difficulties. The most important work planned is the construction of a new double-track line parallel to the existing line.
- The Milan–Lyon line connects Lombardy and Savoy. The infrastructure was built in the 19th century and has been continually renovated. The new HSR will be part of Trans-European Transport Network (TEN-T) 6, Budapest–Lyon. The stretch between Milan and Turin is already operative. The most important work planned for the line is the Monte d'Ambino base tunnel (St. Jean de Maurienne–Susa, 55 km, € 10.5 billion; a base tunnel is a flat railway tunnel that runs through the base of a mountain).
- The Genoa–Basel line connects Liguria with Basel, passing through Simplon and Bern. The new HSR will be 1 of the 2 lines that constitute the Trans-European Transport Network (TEN-T) 24, Rotterdam–Genoa. The most important work involved is the construction of 2 base tunnels: the Lötschberg base tunnel (Frutigen–Raron, 34.6 km, € 7.9 billion), operative since 2007, which links the Bernese Oberland and the Valais with a single tube; and Terzo Valico (Fegino–Novi Ligure, 34 km, € 6.3 billion), currently under construction and expected to be finished by 2021, which will connect Genoa with Milan and Turin.
- The Genoa–Zurich line connects Liguria with Zurich. The new HSR, the second line of the Trans-European Transport Network (TEN-T) 24, Rotterdam–Genoa, will include the Genoa–Milan line and the new Milan–Zurich line. Three new base tunnels are part of the lines

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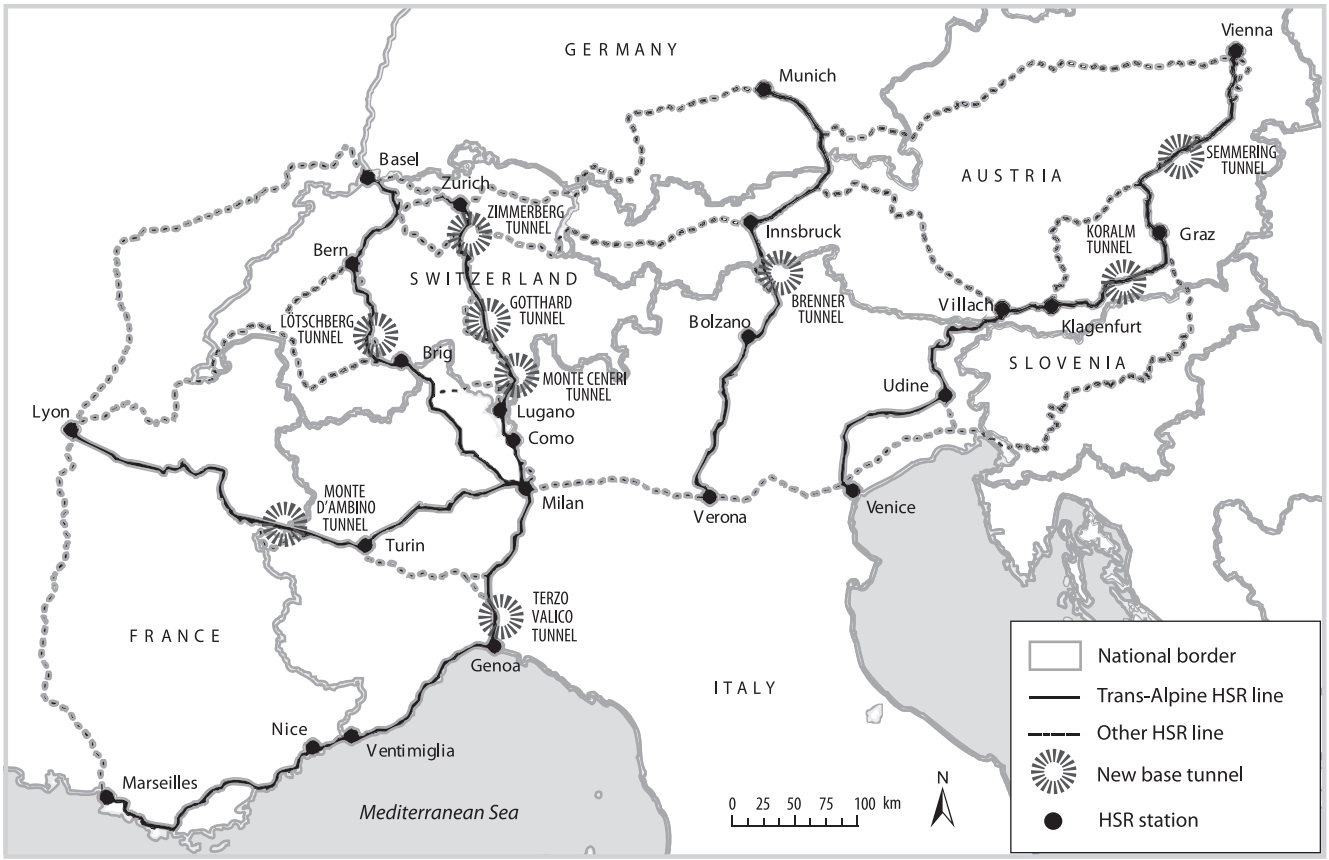
FIGURE 1 Current and planned HSR lines and stations in the Alps. (Map by Elisa Ravazzoli)



Monte Ceneri (Camorino–Vezia, 15 km, € 1.6 billion), which is expected to be finished by 2019; Gotthard (Erstfeld–Bodio, 57 km, € 8.0 billion), completed in 2016; and Zimmerberg (Zurich–Zug, 22 km), which is partially operative between Zurich and Thalwil.

- The Verona–Munich line connects Bavaria to the Veneto, passing through the Lower Inn, Sill, Isarco, and Adige Valleys. It is the central part of the Trans-European Transport Network (TEN-T) 1, Berlin–Palermo. It has 3 sections: the northern access line (Munich–Innsbruck), already operative; the Brenner base tunnel (Innsbruck–Fortezza, 55 km; € 7.9 billion), which is expected to be completed by 2026; and the southern access line (Fortezza–Verona), which is under construction.
- The Venice–Vienna line connects the Veneto to Vienna. It is part of the Trans-European Transport Network (TEN-T) 23, Gdansk–Venice. The Alpine sector includes Lower Austria, Styria, Carinthia, Friuli-Venice Giulia, and Veneto. Two base tunnels will be constructed: Koralm (Sankt Andrä–Frauental an der Laßnitz, 32.9 km, € 5.4 billion), which will improve the link between Styria and Carinthia; and Semmering (Mürzzuschlag–Gloggnitz, 27.3 km, € 3.1 billion), which will connect Styria and Lower Austria.

Shorter railway travel times are likely to make the train more competitive as a transport mode along these trans-Alpine routes (Table 1). This will have implications for travel behavior. It is widely accepted that several factors influence transportation choices, such as cost, number of changes, and reliability; the reduction of travel time is among the most relevant (Sinha and Labi 2007) and was therefore the focus of this study.

Methodology

We created a time-scaled map to project changes in travel times for the Alpine arc before and after the construction of the trans-Alpine HSR lines. Unlike other travel time maps (such as isochrone maps), time-scaled maps consider both time and space. The creation of the time-scaled map is based on the following 3 steps, described in detail below:

1. A database was created with both spatial and travel-time data.
2. MDS was used to transform the physical (geographical) coordinates of the nodes on a map into time coordinates.
3. Finally, a time-scaled map was drawn that visualizes the distances between nodes on a map based on travel-time data.

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TABLE 1 Current and projected travel times by train and car between selected locations.[a)]

Route	Travel time			Travel time difference, train versus car	
	By train, current	By train, projected	By car, current and projected	Current	Projected
Genoa–Basel	05:40	04:13	05:09	+00:31	−00:56
Genoa–Zurich	05:15	03:38	04:40	+00:35	−01:02
Genoa–Marseille	05:39	03:15	04:11	+01:28	−00:56
Milan–Lyon	04:46	02:32	04:57	−00:11	−02:25
Verona–Munich	05:23	03:00	04:35	+00:48	−01:35
Venice–Vienna	07:58	06:33	06:14	+01:44	+00:19

[a)]Sources: SUPSI 2001; Bieger et al 2004; BMVIT 2010; Comune di Genova 2013; Deutsche Bahn 2013; Trenitalia 2013.

Database creation

Spatial information on the trans-Alpine HSR network was organized into a geographical database. The database, which served as the basis for all calculations, contained spatially referenced data, mainly shapefiles in an ESRI format. New shapefiles were created to represent the trans-Alpine HSR network and the other HSR nodes (stations), as well as links (rail lines). The shapefile exemplifying the trans-Alpine HSR lines and HSR stations, including the base tunnels ($n = 9$), were based on railway project drawings (eg BBT SE 2008 for the Brenner HSR). The shapefile representing the other HSR line was based on data from the ETISplus transport policy database (www.etisplus.eu/default.aspx). Figure 1 shows the trans-Alpine HSR network and the other HSR lines linked to the HSR nodes.

Two origin–destination matrices (also called distance matrices) were developed based on current and projected travel times and using as origin and destination the nodes (stations) of the trans-Alpine HSR network. Current travel times, for the shortest distance between 2 given nodes on a workday, were obtained from the online databases of the German and the Italian rail networks (Deutsche Bahn 2013; Trenitalia 2013). In some cases, these involved a direct connection between the 2 nodes, and in others 1 or more transfers were required. Python 2.7 software was used to calculate the shortest routes and ascertain the travel times. For direct connections, the shortest travel time was extrapolated from the websites. For connections that required transfers, travel times were calculated based on the shortest route through linked cities, using Dijkstra's (1959) shortest-path algorithm. Projected travel times between the nodes once the HSR system is operational were obtained from technical reports and specialized websites (SUPSI 2001; Bieger et al 2004; BMVIT 2010; Comune di Genova 2013).

Multidimensional scaling

Based on the distance matrices of current and projected travel times, we used the MDS algorithm to create a time-scaled map, where the distances between the nodes (stations) of the trans-Alpine HSR network are as close as possible to the travel times and not to their physical distances. In this research, the MDS algorithm is used to rescale physical locations of the nodes of the trans-Alpine HSR network into time-scaled locations. There are several MDS algorithms, which differ according to the procedure used. The standard expression of MDS is the objective function for a given set of travel times presented in the following equation (Ahmed and Miller 2007):

$$\mathrm{MIN}_{\{dij\}}\sigma = \sum \left[d_{ij} - f(\delta_{ij})\right]^2$$

where dij are distances, (δ_{ij}) are travel times, and $f(\ )$ is an hypothesized proximity function. For a set of travel times (δ_{ij}), MDS attempts to find a set of points such that distances dij between these points corresponds as closely as possible to the travel times. A zero value for σ means a perfect fit between the travel times and the distances; increasingly positive values of σ indicate increasingly poor fits, meaning that it is difficult to find a set of consistent distance relationships that capture the proximity relations.

In order to perform the MDS we employed the software Matlab. In the process of rescaling of the coordinates, Matlab makes a distinction between *classical* and *nonclassical MDSs*. *Classical MDS* assumes that the data display metric properties, such as physical distances between two objects on a map, so distances in a classical MDS space preserve the intervals and ratios between the proximities as well as possible. In *nonclassical MDS*, data do not represent physical distances but more abstract dissimilarities. For example, instead of indicating the latitude and longitude of a set of cities, the distances between them are expressed in travel time. Thus, nonclassical MDS was more appropriate for this analysis. Nonclassical MDS was performed using the Statistics toolbox in Matlab. The algorithm adopted for this took the geographical coordinates (x longitude, y latitude) of the nodes in the origin-and-destination matrices and replaced them with a new set of coordinates (v, u) based

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on both current and projected travel times. When projected on a map, the resulting rescaled coordinates (time-based coordinates) for current and projected travel times generate a distortion of the map, which exemplifies the effect of the rescaling and the fact that the scale is no longer spatial but temporal.

Visual representation

The distortion of the map was visually represented using the software ArcGIS and the Java software Darcy 2.0 (Cauvin 2005, 2009). ArcGIS was used to calculate the physical (geographical) coordinates of the nodes (stations) of the trans-Alpine HSR network and to reproject the same nodes (rescaled nodes) with the new coordinates generated by MDS based on current and future travel times. The shapefiles of the rescaled nodes were reprojected by applying the transformation tools contained in the GIS. The results were shapefiles of space-based nodes, which correspond to the physical location of the HSR station, and time-space nodes, which correspond to the time scaled locations of the HSR station based on both current and projected travel time. Used together, these shapefiles enabled the visualization of the distortion.

Darcy 2.0 was used to customize the bidimensional regression (Tobler 1994) and to perform the interpolation; the former allows comparison of different points and their respective coordinates, whereas the latter allows estimating of values within 2 known values, enriching the dataset and making the distortion more precise. Together these procedures make it possible to visualize the distortion on a 2-dimensional surface.

To perform the bidimensional regression Darcy 2.0 compared the physical location of space-based nodes with the position of the time-space nodes based on current and projected travel time and provided a distorted image. The distorted 2-dimensional space was later interpolated. The results depend on the level of precision of the interpolation, which is defined by the parameter α. We set an interpolation $\alpha = 20$ with an index of deformation $M = 1.01$ in order to achieve a satisfactory result from the interpolation process. The resulting time-scaled map represents the interpolated and distorted nodes and grids based on the current and projected travel-time distances between each node in the network.

Results

Spatiotemporal effects of HSR lines in the Alps

Figure 2 illustrates the process of rescaling. The output of MDS are displacement vectors, which indicate for each node the passage from a space-based to a time-based dimension, from physical to time-space coordinates. The background shows the original positions of, and physical distances between, the main HSR stations. The application of MDS according to projected travel times causes a shift of the points in the space. As an example, after the adoption of MDS, the current position of the city of Vienna (longitude 16.2332, latitude 47.8028) is shifted 80 km southwest (longitude 15.5859, latitude 47.4002) as the displacement vector shows. Zurich, for example, passes from Switzerland to Germany, and the main eastern Austrian cities move to the southern part of Slovenia. Significant variations are also visible in the western part of the Alps, where Lyon has a new position in Italy, near the Po valley.

The shirking of space, as a function of the time savings, is represented in Figure 3, which shows the distortion of the grid resulted by both the compressions and dilations of space according to the changes in travel times. The peri-Alpine area is condensed on the Italian side, and the distances between nodes along the Po valley, such as between Verona, Milan, and Turin, have shortened. This is accompanied by a substantial shortening of the transversal links, mostly in the western part of the Alps, as shown, for example, in the new positions of Marseille and Lyon and the new shape of the Swiss border.

The eastern part of the Alps is more difficult to interpret. The area along the Vienna–Venice corridor is compressed like other corridors, but the national boundaries of Austria present a swelling of the space, which also involves parts of eastern Italy. This would mean that the introduction of the corridor has significant local consequences in terms of travel times along the HSR lines, but it is not strong enough to influence nearby areas. However, it has to be considered that the map is based only on data related to the major transversal HSR lines, the object of the analysis. It does not consider the east–west corridors, in particular the Vienna–Salzburg–Innsbruck line, which could contribute to reducing the dimensions of Austria and eastern Italy.

Implications for local accessibility: South Tyrol

Key implications for regional accessibility are the potential for remote areas to better connect with the main Alpine and peri-Alpine cities and the ways that the north–south HSR can influence intraregional accessibility in rural areas, considering not only the main train stations but also the entire regional public transport system. As an example, we chose the Autonomous Province of Bolzano/Bozen-South Tyrol (7,400 km^2; 510,000 inhabitants), a mountain province in northern Italy, bordering Austria and Switzerland, whose accessibility might change after the HSR is in operation. The province is characterized by a well-developed transport infrastructure, with 5016 km of roads (including the Brenner highway, which crosses the province north to south; Cavallaro et al 2013) and 287 km of railway (including the Brenner, Venosta Valley, and Pusteria Valley lines; see Figure 4).

The current infrastructure layout creates different conditions in the western and eastern parts of the province. Much of the Adige Valley (up to Merano) in the west is

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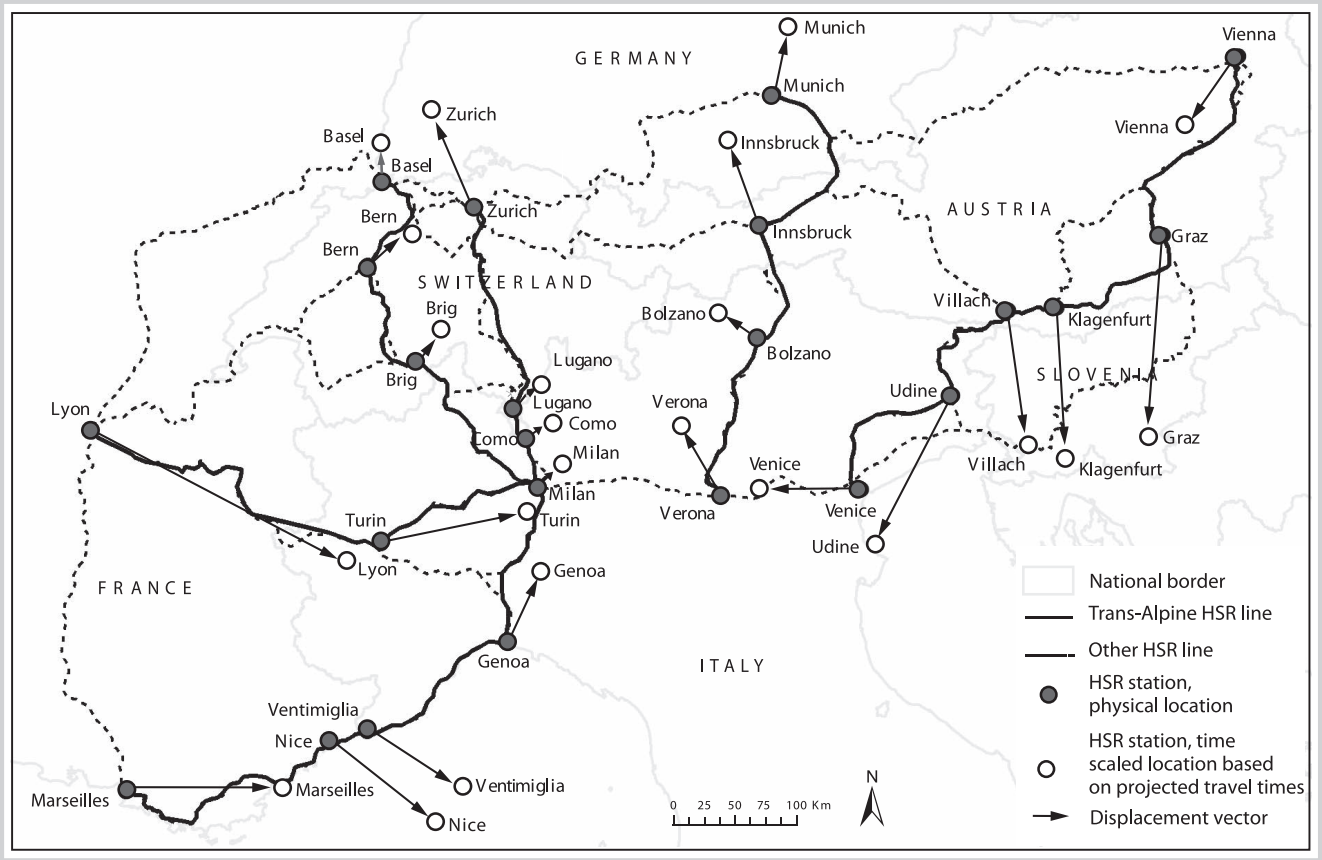
FIGURE 2 Shift of points from physical locations to time-scaled locations. (Map by Elisa Ravazzoli)



accessible from Bolzano, the provincial capital, by a direct railway line. In most cases, this takes less than 1 hour, making train travel competitive with travel by private vehicle. An exception is the upper Venosta Valley (from Merano to Malles), which is currently an unelectrified line and requires a change of trains in the former station, thus leading to an increase in travel time by more than 2 hours. This makes train travel noncompetitive with travel by private vehicle. In contrast, the Pusteria Valley in the east is difficult to access from Bolzano by public transport; the shortest travel times are between 60 and 90 minutes. The necessary change at the Fortezza station increases travel times, making the train noncompetitive with the car.

The municipalities most accessible by private vehicle are located along the north–south axis, the location of the Adige Valley and the main infrastructure, and along the east–west Merano–Bolzano motorway. Longer travel times (between 60 and 90 minutes) are needed to reach other eastern and western locations because of the poorer quality of provincial roads. Nevertheless, private vehicles are currently the most competitive transport means. Using a private vehicle, the average time required to reach the Bolzano HSR station from the provincial municipalities is 55 minutes; only 50 municipalities (out of 115) require less than 45 minutes.

According to public transport timetables (Südtirol Mobil 2014), on average it takes at least 180 minutes from the municipalities of South Tyrol to reach the Bolzano HSR station with the current public transport system. For many municipalities it is possible to reach the Bolzano HSR station in 70 minutes; from 35 municipalities (out of 115), travel times are under 45 minutes. In the future, this is estimated to drop to 125 minutes (for visual representation see Cavallaro et al 2016: 81–82).

Given these local conditions, it is interesting to evaluate the implications for travel time of the introduction of the Brenner HSR line. Figure 5 compares current and projected travel times by public transport and car to Innsbruck, Verona, and Trento from municipalities within 25 km of the Bolzano HSR station.

To reach the Innsbruck station, it currently takes on average 144 min (compared to an average of 118 minutes by car). In the future, the range is expected to decrease 126 minutes on average, while the travel times by car would not see any significant variation. This projection assumes that no intermediate stations are built between Bolzano and Innsbruck. This is an unfavorable condition for municipalities near Fortezza or Bressanone, where passengers will have to depart from Bolzano. Nonetheless, under these conditions, the performance improvements are

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FIGURE 3 MDS-based rescaling of major points along HSR lines. (Map by Elisa Ravazzoli)

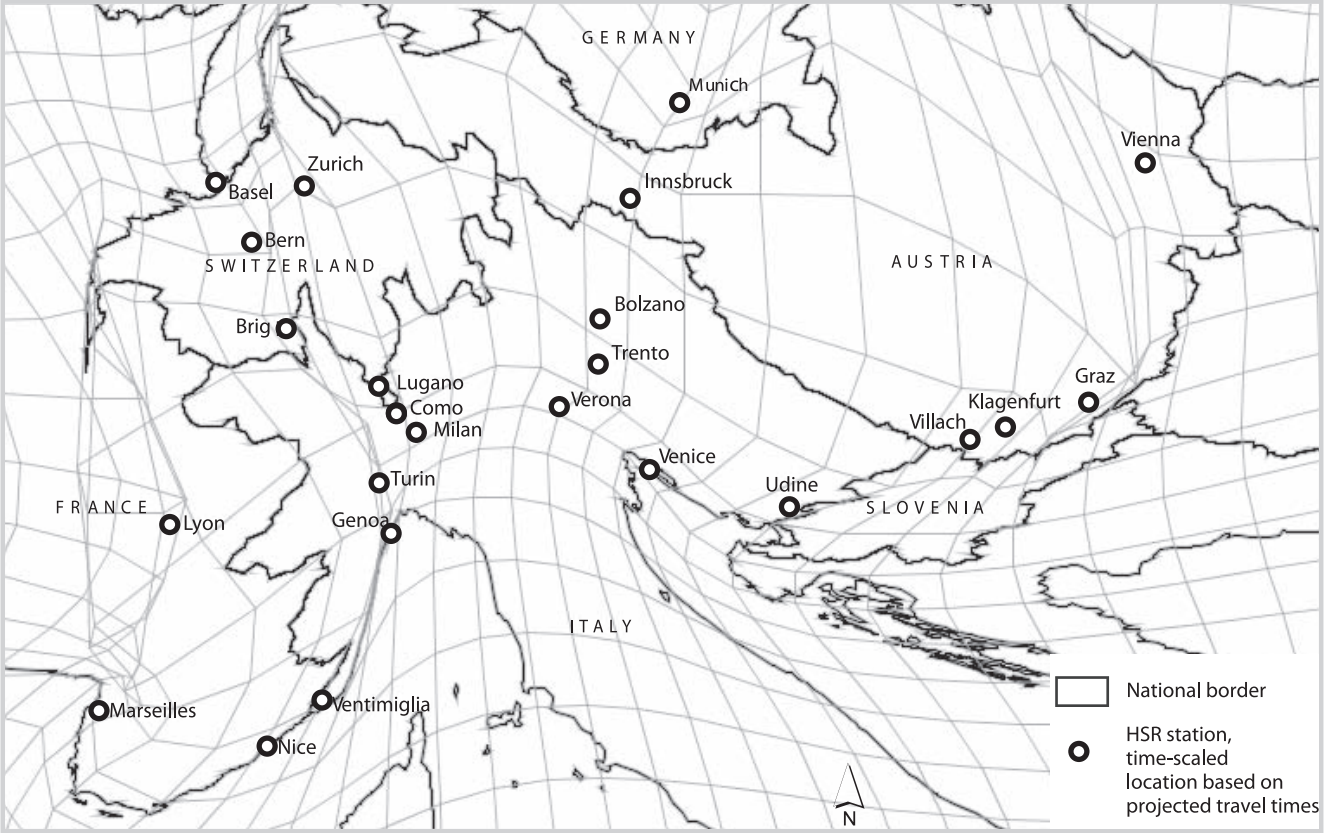

FIGURE 4 South Tyrolean public transport system. (Map by Elisa Ravazzoli)

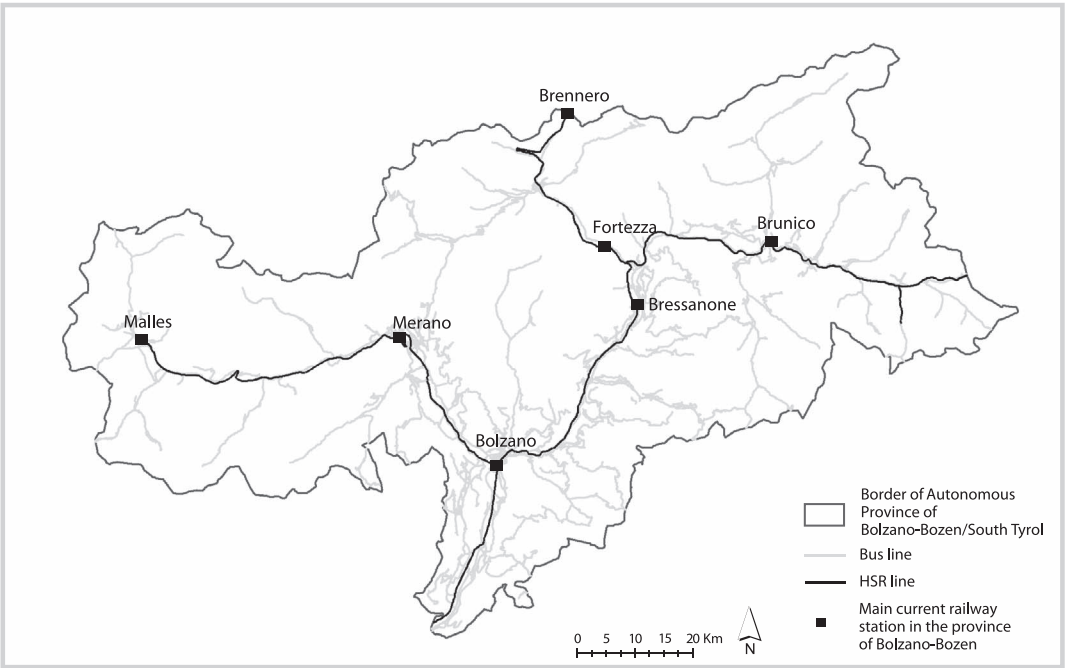

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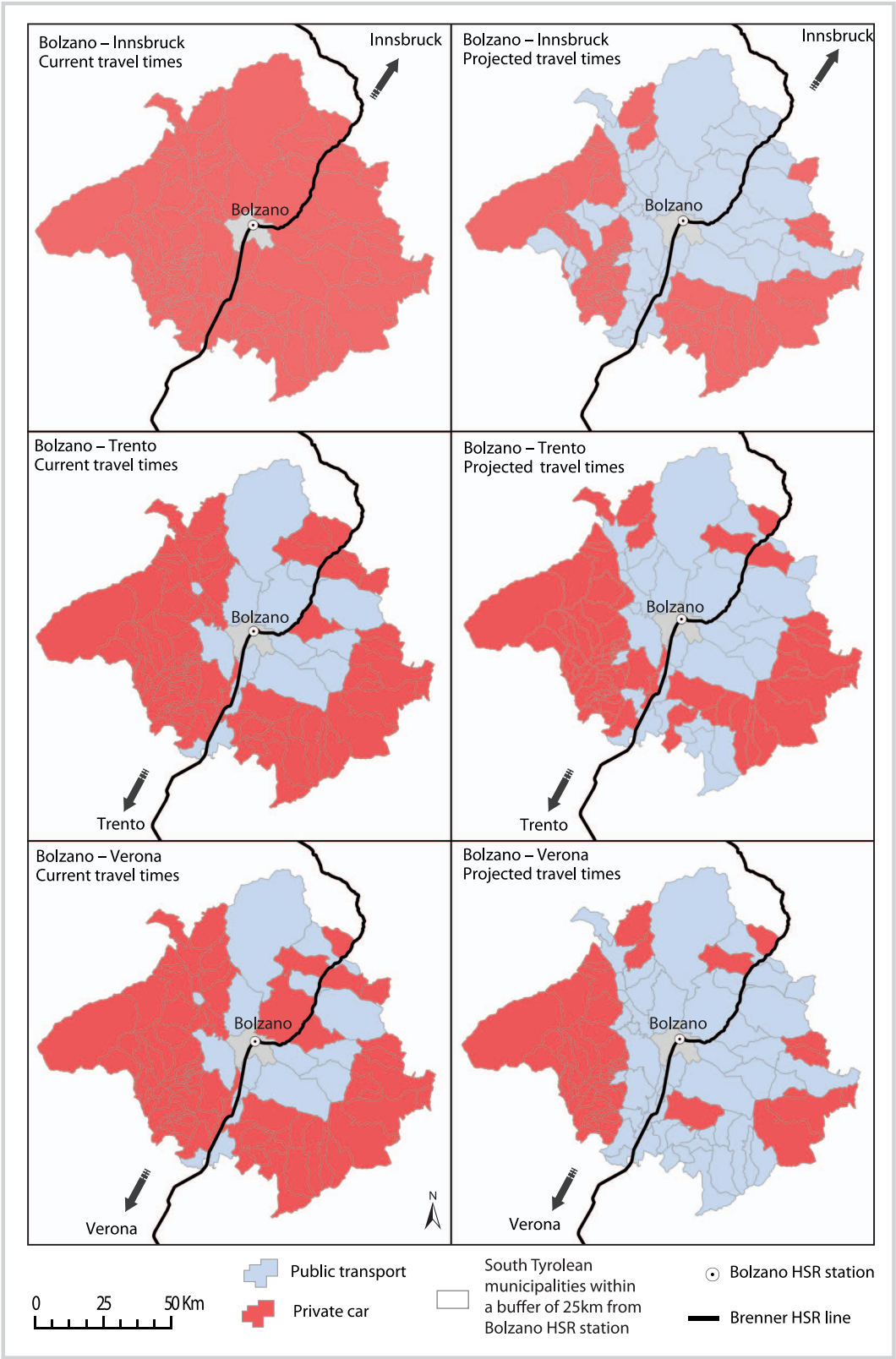
FIGURE 5 Current and projected travel times by car and public transport from the municipalities within a buffer of 25 km from Bolzano HSR station to Innsbruck, Trento, and Verona; shading shows which transport mode is faster. (Map by Elisa Ravazzoli)



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clear, as travel times in several cases (mostly in the central part of the province, closer to the Bolzano HSR station) are even below 90 minutes, shorter than those of private vehicles.

Similar conditions are visible for the connections to Verona (150 km from Bolzano) and to Trento (55 km), even though in these cases the reduction in travel times would not be so significant due to the shorter distances between the 2 train stations and the Bolzano HSR station.

Currently, travel by car is unquestionably more competitive. However, after the introduction of the Brenner HSR line, regional accessibility is expected to change substantially not only for Bolzano's surrounding municipalities but also for those rural areas that are already well connected to the Bolzano HSR station by train (eg the Venosta and Pusteria valleys). Improved accessibility will increase their attractiveness for inhabitants and tourists. At the same time, this may probably lower the attractiveness of the less accessible peripheral zones, making them even more peripheral.

Discussion and conclusions

Travel time is one of the most relevant factors affecting the choice of transport mode (Sinha and Labi 2007). This paper reviewed the expected reduction in travel times between the main cities on the new trans-Alpine HSR network. After the establishment of the HSR lines, the train will become more competitive over long distances than the car, at least in terms of travel times. By using MDS and GIS, a time-scaled map shows how the nodes of the railway network will be brought closer together when the new infrastructure is operative. In a globalized economy characterized by advances in transport infrastructure and increased mobility, time—rather than space—is what interests travelers when choosing a means of transport. In this sense, time-scaled maps are valid tools for representing temporal distances throughout the transport network and for exploring the spatial developments that are expected to occur in the Alps (Perlik et al 2001; Favry and Pfefferkorn 2005).

A broader analysis should be performed, including other components that define the utility function for users, particularly travel costs (Ortúzar and Willumsen 2011). Furthermore, the analysis could be extended to trans-Alpine freight transport (Nocera and Cavallaro 2016b), which should include a discussion about the internalization of transport externalities (to this aim, see Maibach et al 2015). However, even with its limitation to travel times and passenger transport, our analysis illustrates multiple implications. Projected travel times are expected to have a significant impact on travel behavior, environment, economy, and spatial development (Eboli et al 2012).

In terms of travel behavior, regions with "geographic specificities" (Gløersen 2012) such as mountainous regions are especially challenged to link peripheral valley areas with the main transport corridors by providing attractive offers for the last mile. Almost 94% of Alpine tourists travel by car (PSAC 2013). In Europe, improved travel times will positively influence the modal split within tourism mobility. Furthermore, destinations providing environmental-friendly transport facilities can successfully be differentiated from others (Schiefelsbusch et al. 2007), meeting the increasing segment of sustainable tourism (Franch et al 2008). The car-free ski and hiking village of Wengen in the Swiss Bernese highlands is one well-known example.

In terms of environmental consequences, improvement of railway connections is expected to further increase the use of public transport, particularly in rural areas. This contributes to a reduction in the use of private vehicles and to a decrease of congestion, noise, and emission of greenhouse gases and primary pollutants. In particular, CO_2 targets set by the local energy and mobility plans can benefit from this condition. For instance, the provincial energy plan of South Tyrol considers the reduction of transport CO_2 emissions as one of the main issues to be addressed, and the shift from private to public transport can be useful to reach this aim (Provincia Autonoma di Bolzano 2011).

Finally, significant indirect consequences are expected for the economy (new jobs and higher wages, increase in tourism) and land use (increase in built-up areas and in prices; OECD 2002). On the Lötschberg HSR line, after the introduction of the base tunnel, there was not only an increase in demand for public transport (from 7000 to 10,000 passengers per day; Egger 2011), but also changes in the economy. Benefits for the municipalities close to the railway line are visible both in the tourism sector, which has grown considerably (in Brig overnight stays have increased by 14%), and in land use (in Visp housing has increased by 10,000 units). These implications reveal how variations in travel times can support more balanced regional development of mountain areas. Policy-makers should be aware of these implications, and the maps included in this paper can help them to visualize the areas where the most significant changes are expected.

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