On the modal shift from motorway to high-speed rail: evidence from Italy

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Abstract

The development of high-speed rail (HSR) has had a notable impact on modal market shares on the routes on which its services have been implemented. The aim of this study is to analyse whether the HSR expansion in Italy has led to a modal shift from motorway to HSR. We empirically test i) whether HSR openings adjacent to motorway sectors have reduced the total km travelled by light vehicles on these sectors during the period 2001-2017; and ii) whether this reduction has been persistent or even more evident after the opening of on-track competition between two HSR operators. To do so, we carried out a generalized difference-in-differences estimation, using a unique panel dataset that exploits the heterogeneous traffic data within all tolled motorway sectors in a quasi-experimental setting. Our findings reveal that neither HSR openings nor the opening of on-track competition led to a modal shift from motorway to HSR services, as the two transport modes are non-competing. Conversely, HSR expansion had a slightly positive impact on motorway traffic. The extent to which HSR demand could be the result of a modal shift from motorways is a relevant issue in any cost-benefit analysis of HSR investments.

Keywords: High-speed rail, Motorways, Inter-modal competition

JEL Classification Numbers: D78, L92, R41, R58

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1. Introduction

The spread of the railroads has, historically, been one of the main determinants of the urbanization and economic growth of many countries, including the United States (Donaldson and Hornbeck, 2016), India (Donaldson, 2018), Sweden (Berger and Enflo, 2017), Switzerland (Büchel and Kyburz, 2020), and, more recently, China (Diao, 2018; Yu et al., 2019; Huang et al., 2019). In its

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efforts to achieve better social inclusion, cohesion and accessibility, the development of high-speed rail (HSR) has been one of the central features of the European Union's recent transport infrastructure policy (Vickerman, 1997). Indeed, since the end of the twentieth century, many European countries have implemented huge HSR programmes[1] with different characteristics in terms of speed, network integration, type of services and regulation (Campos and De Rus, 2009; Perl and Goetz, 2015).

The rationale underpinning the introduction of HSR has also differed across countries. In some cases, the objective was simply to reduce the travel time between city-pairs (Catalani, 2006), in others it was presented as a "green" solution aimed at limiting the negative environmental impact of air and road transport (Givoni, 2007; Givoni et al., 2009), while in others it was means to facilitate freight transportation (Albalate and Bel, 2012). Each of these objectives has received the support of the European Commission, which in 2011 set specific targets for the development of the HS network (European Commission, 2011) and provided, between 2000 and 2017, 23.7 billion euros in grants to co-finance HSR infrastructure investments across the Member States (European Court of Auditors, 2018).

Today, HSR services have transformed modal market shares on the routes on which they have been implemented (Álvarez-SanJaime et al., 2015), but after more than 50 years of experience of operating HSR around the world, relatively little is known about the nature of its demand (Givoni and Dobruszkes, 2013). Over this period, the majority of research has focused on inter-modal competition between HSR and air services, especially on long point-to-point links, such as the Paris–Lyon (Bonnafous, 1987), Madrid–Barcelona (Román et al., 2007), Madrid–Seville (Jiménez and Betancor, 2012), and London–Paris (Behrens and Pels, 2012) city-pairs. Indeed, studies examining the impact of HSR links on shorter routes, where the car is the competitive means of transport, are, to the authors' knowledge, relatively scarce. Yet, we seek to fill this gap by analysing whether the HSR expansion in Italy has led to a modal shift from its motorways to HSR services in a quasi-experimental setting. To do so, we empirically test, first, whether HSR openings adjacent to motorway sectors have reduced the total km travelled by light vehicles[2] on these sectors during the period 2001-2017; and, second, whether this reduction has been persistent or even more evident after the opening of on-track competition on some adjacent HS and conventional lines between the incumbent *Trenitalia* and the new operator *Nuovo Trasporto Viaggiatori (NTV)*, which entered the HS passenger market in 2012.

This second question is an additional issue of interest in analysing the Italian

[1] At the end of 2017, in the European Union, there were 9 067 km of HS lines and 1 671 km under construction.

[2] We should stress that we exclude the total km travelled by heavy vehicles from our analysis because, although the Italian HSR network was ultimately conceived as a mixed high-speed model equipped with numerous interconnections and line characteristics that would theoretically allow its use by dedicated HS freight trains, to date, not a single freight train has used the new lines (Beria and Grimaldi, 2017).

scenario because it represents the first instance of competition between nonsubsidized HSR operators using the same infrastructure and the same market[3]. Competition provided more HS capacity and forced *Trenitalia* to reduce its average fares (Bergantino, 2015). Moreover, bearing in mind that HSR has reduced the daily commuting travel time in medium and large metropolitan areas by 20-40%, the Italian HSR competes not only with air transport, but also with the car (Cascetta et al., 2011).

The novelty of this paper lies in the fact that we carry out a counterfactual analysis using a unique 17-year panel dataset. This allows us to control for many unobservable confounding factors and to exploit the heterogeneous traffic data within all tolled motorway sectors[4] through a generalized difference-in-differences estimation. Considering the difficulties in forecasting rail project demand (Flyvbjerg et al., 2005; Flyvbjerg, 2007; Börjesson, 2014), our contribution seeks to understand the extent to which HSR demand could result from a modal shift from motorways in order to provide additional evidence for estimating the environmental impact of introducing HSR services (De Rus and Nombela, 2007; De Rus, 2011).

The rest of this article is organized as follows. In Section 2, we present a brief history of the motorway and HSR networks in Italy and we review the literature. In Section 3, we describe our methodological approach and data. In Section 4, we present our results, followed, in Section 5, by our robustness checks. Section 6 critically discusses our findings and Section 7 concludes.

2. The HSR network in Italy and previous evaluations

Italy's first HS service was launched in 1992 between Florence and Rome, with the so-called *Direttissima*, which allowed the 254 km between the two cities to be covered in about two hours. The development of a high-speed/high-capacity network (in Italian, *alta velocità/alta capacità* or AV/AC) was first conceived during the early '90s as an independent system from the rest of the existing network and accessible to light HS rolling stock only (Albalate and Bel, 2012). In 1996, however, the nature of the project changed and it became a mixed high-speed and freight line, including many interconnections with existing conventional lines and capable of hosting freight trains (RFI, 2007).

The Turin–Salerno axis, which took a decade to construct (completed in 2009) and which allowed trains to travel at speeds of 250-300 km/h, provided

[3]On 1 June 2000, the two main divisions of the Italian railway company, infrastructure and services, were separated. Infrastructure management was assigned to *Rete Ferroviaria Italiana* (RFI), while passenger services were assigned to *Trenitalia*. Both are subsidiaries of *Ferrovie dello Stato Italiane* (FSI) and entirely publicly owned. The liberalisation process started in 2003, when the Italian Government implemented the European Directives on rail competition (2001/12/CE, 2001/13/CE, and 2001/14/CE) into the *Decreto Legislativo* n.188 of 8 July 2003.

[4]We refer to those motorway sectors managed by highway concession companies, which represent almost 87% of the national network. Traffic data for the remaining toll-free motorway sectors are not available. See Section 2 for further details.

faster connections between the cities making up what can be considered Italy's *"backbone"* (i.e., Turin, Milan, Bologna, Florence, Rome, Naples and Salerno). The sections at either end of the Milan–Venice axis (i.e., Milan–Brescia and Padua–Venice) were completed in 2016 and operated services at speeds of 200-300 km/h, while the upgrading of the Verona–Bologna line was inaugurated in 2009, raising its speed to 200 km/h.

To date, the national network comprises more than 1 000 km of HS lines[5] (see Appendix Tables A and B for the timeline of opening dates, and see Appendix Figure A for a map of the HSR expansion adjacent to motorway sectors). The supply model adopted by its two operators is a mixed high-speed model in which *Frecciarossa* and *Italo* trains generally operate only on dedicated tracks that can reach speeds of 300 km/h (fully high-speed services), *Frecciargento* (and also *Italo*) trains operate at a maximum of 250 km/h on HS lines where connections with the conventional infrastructure are available (mixed high-speed and conventional services), while *Frecciabianca* trains operate on conventional lines only (fully conventional services)[6].

Italian motorways, instead, underwent a massive expansion in the 1960s and '70s (Ragazzi, 2006). In 2017, the total length constituted 6 003 km of tolled motorway sectors under concession to 25 private, public, or mixed capital companies, while 939 km of toll-free motorway sectors were managed by ANAS, a government-owned company under the control of the Ministry of Infrastructure and Transport (AISCAT, 2017).

Leaving to one side the large number of cost-benefit analyses made of HSR, the introduction of HSR services has primarily encouraged studies of the inter-modal demand competition (Yang and Zhang, 2012; Bergantino and Capozza, 2015; Capozza, 2016), supply competition (Dobruszkes, 2011; Jiménez and Betancor, 2012), and cooperation (Givoni and Banister, 2006; Albalate et al., 2015) between air and rail, stimulated by such questions as airport congestion (Fageda and Flores-Fillol, 2016) and airlines' service quality (Zhang et al., 2019). Likewise, the liberalisation of the rail market has resulted in several studies that focus on the intra-modal competition between rail operators, particularly in the Italian context (Bergantino et al., 2015; Beria et al., 2016). The literature examining the competition between car and rail, on the other hand, is very scant.

Among the few studies that have examined the effect of HSR expansion on car-rail mode substitution, González-Savignat (2004) designed a discrete choice model to evaluate, ex-ante, the impact of the future HSR on current road users in the Madrid–Barcelona corridor. She identified that HSR would become a

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[5] Other HSR projects, such as the central section of the Milan–Venice axis, the Genoa–Milan link, the Naples–Bari link, the Palermo–Messina–Catania link, and three important Alpine lines are under construction or under discussion as regards their redefinition (MEF, 2016, 2017).

[6] *Frecciarossa*, *Frecciargento*, and *Frecciabianca* are the commercial names of *Trenitalia*'s long-distance market services (*"le Frecce"*), while *Italo* is the commercial name adopted by *NTV* trains.

more competitive alternative for business car travellers. In the case of ex-post evaluations, Givoni and Dobruszkes (2013) provided a comprehensive international review by collecting results from studies analysing different markets. They conclude that the reduction in the number of car passengers (due to the introduction of HSR) on the routes examined is in the order of 10-20%. However, in the Madrid–Seville link, car passengers increased by 23% after HSR services begun (European Commission, 1998). Likewise, on Korean and Taiwanese routes, road transport retained high utilization rate after the introduction of HSR services (Cho and Chung, 2008; Cheng, 2010).

In the case of Italy, Cascetta et al. (2011) explored user behaviour on the multimodal Rome–Naples link of 205 km by using a revealed preference survey carried out in March 2008. They found that the percentages of HSR users that actually used the motorway before the HSR was inaugurated were just 7.8% on weekdays, 12.4% on Saturdays, and 14.4% on Sundays. In a study of the whole area influenced by HS lines, Cascetta and Coppola (2015) analysed data gathered by means of on-board counts on HS trains, highways and domestic flights, between 2009 and 2013. The authors concluded that HSR had a direct impact on the modal split of long distance travel demand and showed that total HSR demand increased by 81% during the period of study, while the variation in domestic travel demand by air and highway were substantially different if observed within the HSR catchment area (-29 and -19%, respectively) with respect to their national trends (-7 and -10%, respectively). Moreover, they estimated a broader effect in terms of modal share in the core area: from 25 to 44% for HS services at the expense of airlines (from 10 to 7%) and highways (from 57 to 45%).

However, it should be noted that the above studies are heavily influenced by route-specific characteristics and are conducted over relatively short time spans. Bearing in mind the difficulty in discerning the impact of HSR expansion on car-rail mode substitution from the general trend increase in demand for car travel (Goodwin and Van Dender, 2013), the study we report here adopts a counterfactual approach that seeks to overcome these limitations by taking into consideration a longer time-span of analysis and by exploiting heterogeneous traffic data within a sizeable set of different motorway sectors.

3. Empirical analysis

3.1. Methodology and data

The objective of this study is to empirically test the impact of i) HSR openings and ii) the opening of on-track competition on the total km travelled by light vehicles on adjacent motorway sectors[7]. For this purpose, we collected data for

[7] We define a motorway sector as "adjacent" to an HSR service when both transport modes connect the same city-pairs through largely parallel routes. Indeed, a large part of the HSR network was built next to highways so as to prevent further land consumption (Beria et al., 2018).

52 tolled motorway sectors over the period 2001-2017 (that is, both before and after the HSR expansion), where the treated are those sectors that experienced either an HSR opening on the same route, or the opening of on-track competition on the adjacent HS or conventional line, while the non-treated are those sectors that experienced neither of the two phenomena (see Appendix Figures A and B for a map of the treatment and control groups). Accordingly with the generalized difference-in-differences approach (namely, a "two-way fixed effects" model), each counterfactual is defined by the period before the treatment and by the motorway sectors not affected by the treatment. Then, we estimated the pre- and post-HSR expansion differences in traffic of the treated and non-treated motorway sectors through the following semi-log[8] panel equations:

$$\begin{aligned}\log(Vehicles - Km_{it}) = \beta_0 &+ \beta_1 HSR_{it}^{Opening} + \beta_2 Vehicles_{it} \\ &+ \beta_3 GDP_{it} + \beta_4 Airport\ size_{it} + \beta_5 Sector\ length_{it} \\ &+ \beta_6 Toll_{it} + \beta_7 Fuel_t + \alpha_i + \delta_t + \theta_{it} + \epsilon_{it}\end{aligned} \quad (1)$$

$$\begin{aligned}\log(Vehicles - Km_{it}) = \beta_0 &+ \beta_1 HSR_{it}^{Competition} + \beta_2 Vehicles_{it} \\ &+ \beta_3 GDP_{it} + \beta_4 Airport\ size_{it} + \beta_5 Sector\ length_{it} \\ &+ \beta_6 Toll_{it} + \beta_7 Fuel_t + \alpha_i + \delta_t + \theta_{it} + \epsilon_{it}\end{aligned} \quad (2)$$

where the dependent variable in both equations is the log of the total km travelled by light vehicles[9] ($Vehicles - Km_{it}$) on motorway sector i in year t. The main explanatory variables are:

- $HSR_{it}^{Opening}$ (Equation 1): continuous variable that takes values between 0 and 1 depending on whether a full or partial HS line was opened adjacent to a motorway sector i in year t. It is calculated as the ratio between the km of HSR in operation and the total HSR length, once completed (see Appendix Table A for further details).
- $HSR_{it}^{Competition}$ (Equation 2): continuous variable that takes values between 0 and 1 depending on whether on-track competition between the incumbent and the new operator started on a full or partial HS or conventional line adjacent to a motorway sector i in year t. It is calculated as the ratio between the km of line under competition and its total length (see Appendix Table B for further details).

In both equations, the control variables are:

[8] We adopt a semi-log specification first, because the log transformation of our dependent variable allows to obtain more symmetrically distributed residuals; and second, because it allows to provide clearer economic insights by interpreting how changes in our covariates affect the percentage change in our dependent variable.

[9] Technically, light vehicles are motorcycles and two-axle vehicles with a height above the ground, at the front axle, lower than 1.30 meters.

- $Vehicles_{it}$: light vehicles per capita calculated as the ratio between the number of light vehicles and population of municipalities located within a highway catchment area, i.e., within a 15-km arc distance from exits of a motorway sector i in year t (CERTeT-Bocconi, 2006; Percoco, 2015). Since we cannot observe solely the percentage of km travelled by light vehicles that covered the whole route (i.e., those km travelled by long-distance passengers who are more willing to evaluate HS trains as an alternative mode of transport), this variable aims at capturing an approximation of the impact of commuters living in areas with high highway accessibility on the total km travelled. Similarly, it aims at capturing possible increases in trasport demand potentially due to increases in local populations.

- GDP_{it}: weighted average of gross domestic product per capita (in thousands of euros) in the regions of transit for a motorway sector i in year t (weights are based on the percentage of km of motorway sector located in each region). This variable is a proxy of the economic activity surrounding the highway area.

- $Airport\ size_{it}$: passengers (in millions) carried by domestic flights departing from airports located within a 50-km arc distance from exits of a motorway sector i in year t, which is a standard size of an airport's catchment area (Lieshout, 2012; Suau-Sanchez et al., 2014). This variable is a proxy of the competitive transport sector surrounding the highway area.

- $Sector\ length_{it}$: length (in km) of a motorway sector i in year t.

- $Toll_{it}$: revenues per km travelled (in euro cents) as earned by the highway concession company of a motorway sector i in year t calculated as the ratio between total revenues and total km travelled by vehicles on that sector. Note that motorway sectors managed by the same concessionaire have the same $Toll$ value. This variable is a proxy of toll fare.

- $Fuel_t$: weighted average cost of fuel (in euro cents) in year t calculated as the average national cost of gasoline, diesel, and LPG weighted by the percentage of national light vehicles powered by the three different fuel types.

- α_i, δ_t, θ_{it}: motorway sector, year, and GDP-by-year fixed effects.

Heteroskedasticity- and autocorrelation-consistent standard errors ϵ_{it} are clustered at the highway level, because some motorway sectors belong to the same highway. Data of our dependent variable ($Vehicles - Km$), as well as *Sector length* and $Toll$ data, were obtained from AISCAT (*Associazione Italiana Società Concessionarie Autostrade e Trafori*, the concessionaires' association), which provides detailed annual reports on the operations of each tolled motorway sector. $HSR^{Opening}$ and $HSR^{Competition}$ data are based on Bergantino et al. (2015), Beria et al. (2018), and taken from RFI and NTV websites, and the operators' financial statements. Data for $Vehicles$, i.e., the number of light vehicles and population at municipality level, were obtained from ACI (*Automobile Club d'Italia*) and ISTAT (*Istituto Nazionale di Statistica*), respectively, while municipalities located within a 15-km arc distance from motorway exits were identified from the *Automap* website. *GDP* data were also obtained from ISTAT, while *Airport size* data were provided by Eurostat. Finally, data for *Fuel*, i.e., the average cost of gasoline, diesel, LPG, and the relative number of light vehicles at national level, were obtained from MiSE (*Ministero dello sviluppo economico*) and ACI[10].

It should be noted that to avoid an overly unbalanced panel dataset, we excluded from our dataset *A35 Milano–Brescia*, *A58 Tangenziale esterna di Milano*, and *A36 Pedemontana Lombarda* motorway sectors because they started their operations at the end of our period of analysis (in 2014, 2015, and 2016, respectively); that is, after the opening of several HSR sections. Likewise we also excluded *T1 Traforo del Monte Bianco*, *T2 Traforo del Gran S. Bernardo*, and *T4 Traforo del Fréjus* Alpine tunnels because their characteristics (e.g., traffic, length, and toll fare) are very different from those of the other motorway sectors, and as such, they are not suitable to be in the control group. Finally, we excluded the *A1 Firenze–Roma* motorway sector because the competitive HS line connecting the two cities had been in operation before 1992 (see Appendix Table C for a list of motorway sectors considered in the study).

The rationale for using $HSR^{Opening}$ as our treatment variable is the fact that it can capture any degree of local competition between motorway and HSR because both transport modes connect the same city-pairs located at relatively short distances from each other. The only exception is the Verona–Bologna link where the motorway sector connects the two cities passing through Modena.

It is worth noting that unlike previous studies that opted to measure the effect of intra-modal competition in terms of market shares, our $HSR^{Competition}$ treatment variable considers the competition between HSR operators as a measure of augmented supply at lower fares. Indeed, although *NTV*'s market penetration has been especially rapid[11], *Trenitalia* also reacted by increasing both its capacity and demand[12]. The literature attributes this marked increase in passenger numbers to the maturity of the HSR network as well as to the com-

[10] AISCAT data were retrieved from `http://www.aiscat.it/english/pubblicazioni.htm?ck=1&nome=pubblicazioni&idl=4`. ACI data were retrieved from `http://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/autoritratto.html` and their light vehicle data, at both municipality and national levels, are missing for the year 2001; therefore, they have been considered the same as those for 2002. ISTAT data were retrieved from `http://dati.istat.it/`. Eurostat data were retrieved from `https://ec.europa.eu/eurostat/web/transport/data/database`. MiSE data were retrieved from `https://dgsaie.mise.gov.it/prezzi_carburanti_annuali.php` and *Fuel* data are at national level because more disaggregated data are only available from 2015 onwards. Finally, RFI website is `http://www.rfi.it/rfi/LINEE-STAZIONI-TERRITORIO`, *NTV* website is `https://italospa.italotreno.it/societa/la-storia/cinque-anni-di-italo.html`, while *Automap* website is `https://www.automap.it/`.

[11] *NTV* passengers rose from 2 million in 2012 to 12.8 million in 2017. In 2013, *NTV* held the 25% of the HS market share (Bergantino et al., 2015; Nuovo Trasporto Viaggiatori, 2017).

[12] For instance, on the Milan–Rome–Naples line, the supply of HS *Trenitalia* services rose from 71 daily departures in 2009 to 89 in 2012 (Cascetta and Coppola, 2014). On its commercial long-distance services, *Trenitalia* passengers rose from 18.7 million in 2010 to 45 million in 2014 (Beria and Grimaldi, 2011; Dell'Alba and Velardi, 2015).

petition effects (Cascetta and Coppola, 2015). Following the entry of the new operator, travellers enjoyed not only an average reduction in HS fares but also a differentiation of tariffs (e.g., from simple 1st and 2nd classes to the Executive, Business, Premium, and Standard classes), a differentiation of prices (e.g., Base, Economy, and Super-Economy prices), new stations of origin and destination (e.g., Rome Tiburtina and Milan Porta Garibaldi secondary stations), and a better quality of ancillary services (e.g., Wi-Fi and agreements with local tourist attractions). Since we can reasonably expect that all these changes favoured travellers with a low willingness to pay[13], the coefficient associated with $HSR^{Competition}$ seeks to capture whether on-track competition led to a stronger modal shift from motorway to HSR services.

To reinforce the argument for the use of the difference-in-differences methodology, a graphical representation of the common trend assumption is needed. To this end, Figure 1 plots the temporal pattern of the treatments that we exploit, together with the evolution of the average number of km travelled on two different types of motorway sector: the first (solid line) includes the treated sectors that experienced either an HSR opening on the same route (Figure 1a), or the opening of on-track competition on the adjacent HS or conventional line (Figure 1b); the second (dashed line) includes the non-treated sectors that experienced neither of the two phenomena. Even though motorway traffic is, on average, significantly higher in the treated groups, it is clear how the two trends in both scenarios follow a very similar path not only before treatment, but throughout all the period of analysis. Graphically, there is no clear evidence of the possible impact of $HSR^{Opening}$ or $HSR^{Competition}$ in reducing motorway traffic. Note that the 2013 fall in motorway traffic and the subsequent recovery seem more pronounced in the treated groups.

Finally, it could be argued that the non-random route placement of HSR might bias our estimates. In relation to this issue, we can plausibly assume that, conditional on the controls and fixed effects in our quasi-experimental setting, $HSR^{Opening}$ and $HSR^{Competition}$ are exogenous with respect to the total km travelled by light vehicles on the adjacent motorway sectors.

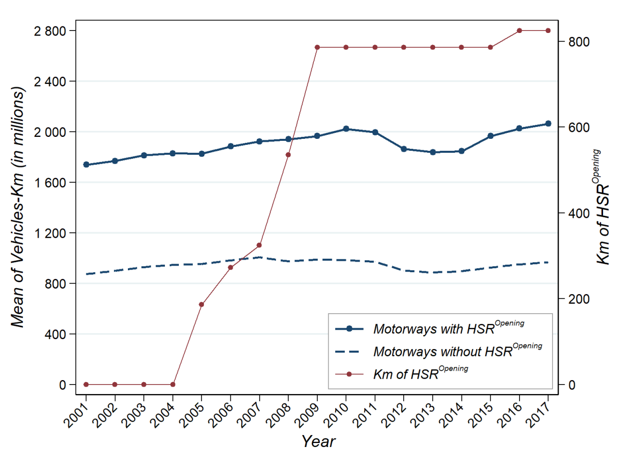
One reason for this is that the decision was taken to build a large part of the HSR network next to highways so as to prevent further land consumption (Beria et al., 2018). Thus, when the route plan is based primarily on geographical factors (e.g., topography and geomorphology) so as to minimize construction costs, the possible endogeneity caused by the non-random location is significantly reduced (Faber, 2014; Yu et al., 2019).

Moreover, the decision on where to locate HSR was also driven by the need to complete the TEN-T corridors, coordinated and co-financed by the European Union (European Court of Auditors, 2018). Designed initially in the '90s (Vick-

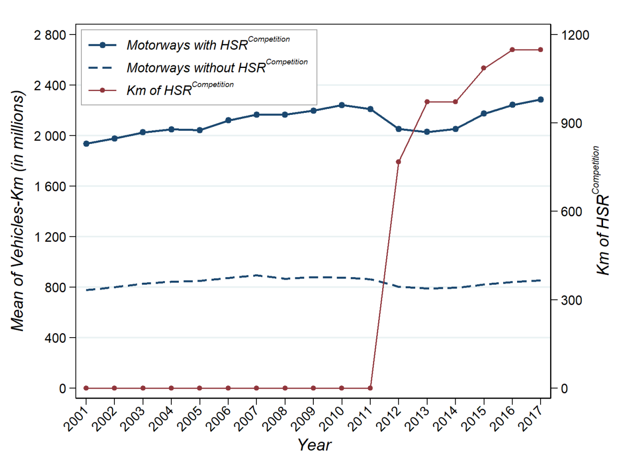
[13] Direct competition between the two HSR operators led to an average fare reduction of 31% in one year and 34% over two years, allowing passengers with less willingness to pay to access HSR services (Cascetta and Coppola, 2014, 2015). Consistent with this, Beria et al. (2016) showed that between September 2013 and December 2014 the incumbent reduced its economy class prices by about 15% on the Milan–Ancona route.

Figure 1: Evolution of the average number of km travelled by light vehicles on motorway sectors with and without either $HSR^{Opening}$ or $HSR^{Competition}$, 2001-2017

(a) $HSR^{Opening}$



(b) $HSR^{Competition}$



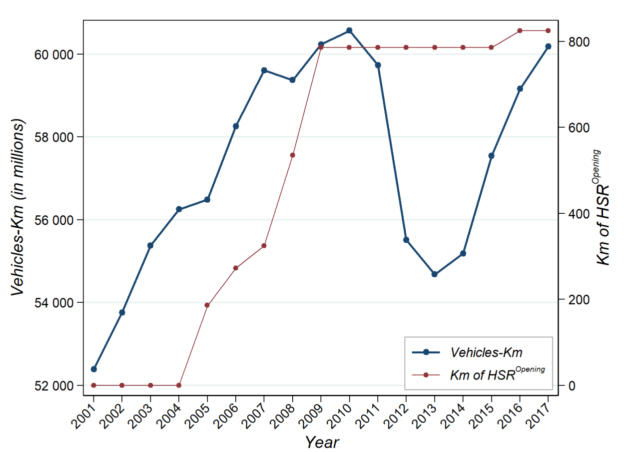
erman et al., 1999), they consist of nine core corridors of road, rail, airport, and port infrastructure aimed at promoting long-distance and high-speed intermodal routes across Europe by 2030. All of the Italian HSR network is built along four of these corridors, which cross the country from north to south and from west to east: the Scandinavian–Mediterranean corridor, the Mediterranean corridor, the Rhine–Alpine corridor, and the Baltic–Adriatic corridor (European Parliament and Council, 2013). Since TEN-T investments are focused essentially on achieving faster, more efficient freight transportation, the HSR location can reasonably be assumed to be exogenous with respect to the total km travelled by light vehicles on the adjacent motorway sectors because our analysis excludes heavy vehicles.

3.2. *Trends and descriptive statistics*

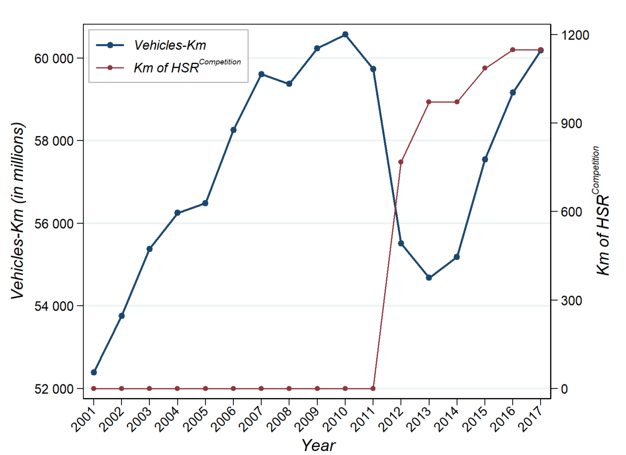
For the period 2001-2017, Figure 2 plots the evolution of the total km travelled by light vehicles on the national tolled motorway network vs. the expan-

Figure 2: Evolution of the total km travelled by light vehicles on motorway sectors vs. the expansion of $HSR^{Opening}$ and $HSR^{Competition}$, 2001-2017

(a) $HSR^{Opening}$



(b) $HSR^{Competition}$



sion of $HSR^{Opening}$ (Figure 2a) and $HSR^{Competition}$ (Figure 2b), showing the temporal pattern of the treatments that we exploit. After peaking in 2010, motorway traffic experienced a slump until 2013, coinciding with the maximum number of km of HS lines in operation. However, over the next 4 years the traffic volume recovered its previous level. This pattern suggests the importance of disentangling the possible impact of HSR expansion in reducing motorway traffic from other confounding factors, such as the global economic crisis. The same explanation applies to Figure 2b, where both the expansion of on-track competition (started in 2012), and the total km travelled by light vehicles show a parallel increasing trend from 2013 onwards.

Table 1 reports the descriptive statistics for the variables in Equation 1 (Panel A) and Equation 2 (Panel B), differentiated for the treatment and control groups previously described. On average, the logarithm of the total km travelled by light vehicles is found to be larger on motorway sectors that experienced either an HSR opening on the same route, or the opening of on-track competition on the adjacent HS or conventional line. As expected, the average GDP per capita and the number of passengers carried by domestic flights are higher in the area surrounding these sectors. In contrast, the average number of light vehicles per capita is lower for municipalities located within the highway catchment area of treated sectors, as is the average revenue per km travelled. Finally, the average sector length is almost the same for the two groups in Panel A (but it differs in Panel B), while the average cost of fuel is the same given that it is

Table 1: Descriptive statistics

Panel A	Mean and Standard deviation		Test of significance of difference
	With $HSR^{Opening}$	W/out $HSR^{Opening}$	
$\log(Vehicles - Km)$	7.300 (0.740)	6.504 (0.890)	***
$HSR^{Opening}$	0.554 (0.470)	0 (0.000)	***
$Vehicles$	0.604 (0.052)	0.656 (0.227)	**
GDP	30.219 (5.121)	28.361 (5.413)	***
$Airport\ size$	7.810 (5.178)	2.324 (3.151)	***
$Sector\ length$	103.82 (56.81)	100.22 (58.60)	
$Toll$	6.979 (1.599)	8.061 (3.312)	***
$Fuel$	128.65 (21.75)	128.84 (21.69)	

Panel B	Mean and Standard deviation		Test of significance of difference
	With $HSR^{Competition}$	W/out $HSR^{Competition}$	
$\log(Vehicles - Km)$	7.409 (0.747)	6.436 (0.845)	***
$HSR^{Competition}$	0.262 (0.422)	0 (0.000)	***
$Vehicles$	0.606 (0.046)	0.658 (0.232)	**
GDP	30.007 (4.427)	28.327 (5.592)	***
$Airport\ size$	5.977 (5.161)	2.550 (3.486)	***
$Sector\ length$	122.75 (63.86)	94.91 (55.24)	***
$Toll$	6.904 (1.539)	8.135 (3.366)	***
$Fuel$	128.65 (21.74)	128.85 (21.69)	

Notes: Significance values: ***p<0.001, **p<0.01, *p<0.05.

calculated at the national level. The table also reports the significance of the test of difference in mean.

4. Results

Tables 2 and 3 report the baseline regression results for Equations 1 and 2, respectively. Models (1) and (2) are pooled OLS estimations. Models (3) and (4) add fixed effects to control for all the different time-invariant factors that may directly affect traffic volumes across motorway sectors. Models (5) and (6) include year dummies to control for the common time trend, such as the impact of the global economic crisis on motorway traffic. Models (7) and (8) also add GDP-by-year fixed effects to capture any regional shocks that might influence the economic activity surrounding the highway area. $Toll$ and $Fuel$ variables could be relevant in explaining car travel demand, however, it might be argued that they may be endogenous with respect to the total km travelled by light vehicles. Therefore, Models (1), (3), (5) and (7) seek to show that these two variables do not affect our results. Indeed, when excluded, the estimated coefficients are not significantly different to the values obtained when they are

Table 2: Effect of $HSR^{Opening}$ on the total km travelled by light vehicles on motorway sectors (baseline estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Opening}$	0.275	0.297	0.084***	0.082***	0.050**	0.050**	0.041**	0.040*
	(0.190)	(0.194)	(0.020)	(0.020)	(0.020)	(0.020)	(0.019)	(0.020)
$Vehicles$	-1.204***	-0.907***	0.211**	0.157	0.147*	0.162	0.113	0.162
	(0.223)	(0.269)	(0.095)	(0.137)	(0.082)	(0.133)	(0.077)	(0.140)
GDP	0.015	0.017	0.012***	0.015***	0.013*	0.012	0.010*	0.006
	(0.017)	(0.017)	(0.004)	(0.005)	(0.007)	(0.008)	(0.006)	(0.009)
$Airport\ size$	0.058***	0.053***	0.014	0.014	-0.018**	-0.018**	-0.010	-0.010
	(0.016)	(0.016)	(0.010)	(0.010)	(0.008)	(0.008)	(0.008)	(0.008)
$Sector\ length$	0.010***	0.010***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$Toll$		-0.044		0.007		-0.002		-0.007
		(0.031)		(0.008)		(0.007)		(0.007)
$Fuel$		0.002		-0.000				
		(0.002)		(0.000)				
$Constant$	5.798***	5.702***	5.042***	4.958***	5.063***	5.096***	5.150***	5.270***
	(0.545)	(0.648)	(0.292)	(0.271)	(0.353)	(0.371)	(0.311)	(0.368)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.653	0.666	0.386	0.390	0.554	0.555	0.580	0.583

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

included. For simplicity, in this section we only discuss the estimates obtained using Model (8) because it is the most complete and extended specification in relation to our data, as confirmed by a comparison of R^2 values and standard errors[14].

In Table 2, the coefficient associated with $HSR^{Opening}$ shows that HSR expansion did not lead to a modal shift from motorway to HSR services, since it is positive and statistically significant at the 10% level. Based on the semi-log regression interpretation provided by Thornton and Innes (1989), this coefficient indicates that, holding constant the other variables, a 10 percentage points increase in HSR length leads, on average, to a 0.41% increase in the total km travelled by light vehicles on the adjacent motorway sectors. Thus, our first interpretation is that the two transport modes are non-competing. As for the relationship between our control variables and the dependent variable, the $Vehicles$, GDP, and $Airport\ size$ coefficients present the expected sign. Indeed, it is reasonable for an increase in both the number of light vehicles per capita and the average GDP per capita in the surrounding area of motorway sectors to produce an increase in traffic volumes. On the other hand, it is reasonable for an increase in the number of passengers carried by domestic flights to induce a fall in the total km travelled by light vehicles, meaning that an improvement in the capacity of the airline sector may have a positive impact on traffic reduction. However, neither value is statistically significant. The $Sector\ length$ variable shows that an additional km of motorway is associated with an average 1.11% increase in the total km travelled by light vehicles. Finally, the $Toll$ variable is not significant, although its coefficient also presents the expected sign[15].

In Table 3, the coefficient associated with $HSR^{Competition}$ shows that the opening of on-track competition between the incumbent *Trenitalia* and the new operator NTV did not lead to a modal shift from motorway to HSR services either. Indeed, the coefficient is still positive and statistically significant at the 10% level. In this case, the coefficient indicates that a 10 percentage points increase in the length of HS or conventional lines subject to intra-modal competition leads, on average, to a 0.59% increase in the total km travelled by light vehicles on the adjacent motorway sectors. Coherent with our previous interpretation, if the two transport modes are non-competing, it is reasonable to expect the $HSR^{Competition}$ coefficient to be larger than the $HSR^{Opening}$ coefficient because the former captures a delayed effect of the earlier treatment. The control variables present very similar outcomes to those reported above and the same explanations apply.

Thus, the empirical evidence provided by our results, so far, suggests that

[14] Note that moving from the most conservative Model (1) to the most extended Model (8), the magnitude of the coefficients associated with $HSR^{Opening}$ decreases without leading to an increase in the standard error. Most importantly, the coefficients remain positive and statistically significant.

[15] Note that the loss of statistical significance of the control variables is due to the saturation of the models through the inclusion of the full sets of motorway sector, year, and GDP-by-year fixed effects, as they capture most of the variability.

Table 3: Effect of $HSR^{Competition}$ on the total km travelled by light vehicles on motorway sectors (baseline estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Competition}$	0.305*	0.348*	0.064**	0.060**	0.062*	0.062*	0.059*	0.057*
	(0.173)	(0.176)	(0.026)	(0.027)	(0.032)	(0.032)	(0.032)	(0.033)
$Vehicles$	-1.203***	-0.899***	0.201*	0.147	0.153*	0.165	0.123	0.169
	(0.221)	(0.268)	(0.100)	(0.145)	(0.082)	(0.130)	(0.075)	(0.134)
GDP	0.015	0.017	0.011***	0.015***	0.014*	0.013	0.011*	0.007
	(0.017)	(0.017)	(0.004)	(0.005)	(0.007)	(0.009)	(0.006)	(0.009)
$Airport\ size$	0.063***	0.058***	0.021*	0.021*	-0.014*	-0.014	-0.006	-0.005
	(0.015)	(0.016)	(0.011)	(0.011)	(0.008)	(0.008)	(0.007)	(0.007)
$Sector\ length$	0.010***	0.009***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.003)
$Toll$		-0.045		0.006		-0.002		-0.006
		(0.031)		(0.008)		(0.007)		(0.007)
$Fuel$		0.002		-0.000				
		(0.002)		(0.000)				
$Constant$	5.801***	5.698***	5.055***	4.954***	5.028***	5.053***	5.112***	5.225***
	(0.549)	(0.646)	(0.308)	(0.279)	(0.353)	(0.372)	(0.312)	(0.370)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.652	0.665	0.375	0.379	0.558	0.558	0.585	0.588

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

the increasing demand for HSR services is not the result of a modal shift from motorways. In all likelihood, it is the result of induced demand (i.e., the amount of new demand originating from travellers that did not travel at all before the introduction of HSR or who have increased the frequency of their trips thanks to HSR) and mode substitution from other modes of transport. Yet, the slightly positive impact of HSR expansion on motorway traffic may have been due, first, to a positive impact of HSR on surrounding economic activities, which could have led to an increase in the total number of car journeys along those routes; and, second, to a negative impact of HSR on conventional rail services, which could have led to an unintended increase in car dependency (see Section 6 for a more detailed discussion).

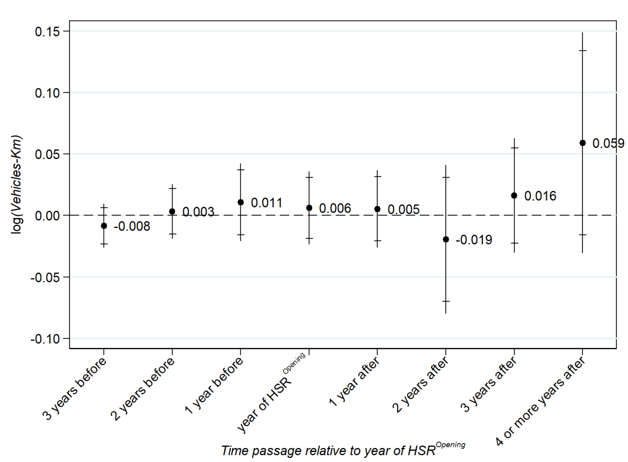
5. Robustness Checks

5.1. Parallel trend assumption and timing of the effects

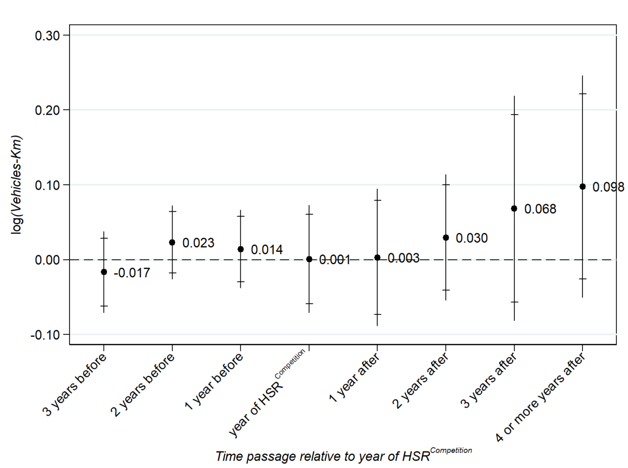
To provide evidence of the reliability of our previous estimates, we need to check the validity of the specifications. The key assumption is the parallel pre-treatment trend. That is, before treatment, the total km travelled by light

Figure 3: Timing of $HSR^{Opening}$ and $HSR^{Competition}$ effects on the total km travelled by light vehicles on motorway sectors

(a) $HSR^{Opening}$



(b) $HSR^{Competition}$



Notes: Vertical bands represent ± 1.645 and ± 1.96 times the standard error of each point estimate.

vehicles on motorway sectors that experienced either an HSR opening on the same route, or the opening of on-track competition on the adjacent HS or conventional line, should present no significant differences with respect to the total km travelled on motorway sectors that experienced neither of these two events. To verify this assumption, and to investigate the timing of the effects, we augmented the difference-in-differences regressions with leads and lags before and after both treatments, as proposed by Autor (2003). To facilitate visualization, Figure 3 shows the plots of the lead and lag coefficients with 90% and 95% confidence intervals for our preferred Model (6) of both Appendix Tables D and E.

The coefficients for the three years before the introduction of both treatments are close to zero and not statistically significant, which verifies the parallel pre-treatment trend assumption. Between the year of $HSR^{Opening}$ and $HSR^{Competition}$ and all the subsequent years, the coefficients fluctuate with an increasing trend between 0.006-0.059 and 0.001-0.098 log points, respectively, indicating that the HSR expansion took some time to be sufficiently mature to induce an unintended growth of traffic volume; however, they are still not statistically significant. Incidentally, what matters here is that we can exclude any reverse causality issue, as the two patterns provide robust evidence that it is the HSR expansion that led to an increase in motorway traffic rather than the other way round.

5.2. Placebo test

Table 4: Effect of $HSR^{Opening}$ on the total km travelled by light vehicles on motorway sectors (placebo estimates)

	$\log(Vehicles - Km)$							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Opening}$	-0.483***	-0.482***	0.012	0.011	-0.010	-0.011	-0.004	-0.006
	(0.156)	(0.164)	(0.042)	(0.043)	(0.044)	(0.043)	(0.041)	(0.039)
$Vehicles$	-1.110***	-0.853***	0.162*	0.099	0.122	0.138	0.089	0.141
	(0.254)	(0.299)	(0.089)	(0.131)	(0.073)	(0.124)	(0.068)	(0.130)
GDP	0.010	0.013	0.009*	0.014***	0.012	0.011	0.009	0.005
	(0.016)	(0.016)	(0.004)	(0.004)	(0.007)	(0.008)	(0.006)	(0.008)
$Airport\ size$	0.067***	0.062***	0.016	0.016	-0.018**	-0.018**	-0.009	-0.009
	(0.014)	(0.014)	(0.010)	(0.010)	(0.009)	(0.009)	(0.008)	(0.008)
$Sector\ length$	0.009***	0.009***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)
$Toll$		-0.040		0.007		-0.002		-0.007
		(0.032)		(0.008)		(0.007)		(0.007)
$Fuel$		0.004**		0.000				
		(0.002)		(0.000)				
$Constant$	5.945***	5.588***	5.143***	4.996***	5.091***	5.124***	5.176***	5.299***
	(0.519)	(0.595)	(0.326)	(0.295)	(0.369)	(0.384)	(0.318)	(0.371)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.668	0.680	0.362	0.368	0.546	0.547	0.575	0.578

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

Methodologically, our difference-in-differences estimates rely on the assumption that, in the absence of both $HSR^{Opening}$ and $HSR^{Competition}$, the differences in the total km travelled by light vehicles on motorway sectors between treatment and control groups would have remained constant. To assess the validity of this assumption, we perform a falsification test by randomly assigning our treatments to motorway sectors that, in reality, experienced neither of the two events. In so doing, the true treated motorway sectors fall within the control group. If our baseline estimates in Section 4 are correctly reflecting the causal effect of HSR expansion on motorway traffic, we would expect the placebo estimates to be close to zero. Tables 4 and 5 report the placebo regressions. Again, limiting the discussion to Model (8) only, the coefficients associated with $HSR^{Opening}$ and $HSR^{Competition}$ are close to zero (-0.006 and -0.003, respectively) and not statistically significant, which verifies the validity of our identification strategy.

Table 5: Effect of $HSR^{Competition}$ on the total km travelled by light vehicles on motorway sectors (placebo estimates)

	$\log(Vehicles - Km)$							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Competition}$	-0.380**	-0.337*	-0.035	-0.039	-0.013	-0.014	-0.003	-0.003
	(0.160)	(0.168)	(0.037)	(0.039)	(0.042)	(0.042)	(0.038)	(0.039)
Vehicles	-1.157***	-0.911***	0.185*	0.118	0.123	0.138	0.088	0.139
	(0.243)	(0.281)	(0.099)	(0.142)	(0.080)	(0.132)	(0.072)	(0.136)
GDP	0.012	0.015	0.006	0.012***	0.012	0.011	0.009	0.005
	(0.017)	(0.017)	(0.004)	(0.004)	(0.007)	(0.008)	(0.006)	(0.009)
Airport size	0.066***	0.062***	0.018*	0.018*	-0.017**	-0.017*	-0.009	-0.009
	(0.015)	(0.015)	(0.009)	(0.010)	(0.008)	(0.009)	(0.009)	(0.008)
Sector length	0.010***	0.009***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Toll		-0.039		0.008		-0.002		-0.007
		(0.032)		(0.009)		(0.007)		(0.007)
Fuel		0.003*		-0.000				
		(0.002)		(0.000)				
Constant	5.903***	5.613***	5.182***	5.022***	5.097***	5.129***	5.177***	5.298***
	(0.551)	(0.628)	(0.323)	(0.293)	(0.374)	(0.386)	(0.322)	(0.373)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.654	0.665	0.366	0.373	0.547	0.547	0.575	0.578

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

5.3. Stable unit treatment value assumption

To provide evidence that a possible violation of the *stable unit treatment value assumption* (SUTVA) is not affecting our estimates, we need to perform an additional robustness check. This assumption states that the potential outcome of one unit should be unaffected by the assignment of the treatment to the other units. In our quasi-experimental setting, this means that the total km travelled by light vehicles on each motorway sector should not be influenced by $HSR^{Opening}$ and $HSR^{Competition}$ on other motorway sectors. This "no interference" condition is rarely verified in transport analyses because all routes within an highway network are connected to each other.

For instance, if we imagine the HSR network as a *hub-and-spoke* system, surrounding conventional rails (*spokes*) might act as feeders by linking to the nodes of the HSR routes (*hubs*) passengers who need to be connected with long-haul and faster trains. If this is the case, motorway sectors adjacent to those conventional rails might experience a reduction in the total km travelled.

To check that this possible phenomenon is not affecting our results, we perform the same analysis as in Section 4 but drop from the dataset all the non-treated motorway sectors directly connected to the nodes of the HSR routes. By so doing, we are able to compare the total km travelled by light vehicles on the treated motorway sectors with respect to those travelled on a sub-sample of control motorway sectors that are distant from the treated, for which the

Table 6: Effect of $HSR^{Opening}$ on the total km travelled by light vehicles on motorway sectors (sub-sample estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Opening}$	0.453**	0.499**	0.088***	0.088***	0.055**	0.055**	0.043**	0.043**
	(0.177)	(0.194)	(0.020)	(0.021)	(0.021)	(0.020)	(0.019)	(0.020)
$Vehicles$	-1.124***	-1.041***	0.302***	0.211	0.209**	0.199	0.192***	0.268
	(0.237)	(0.326)	(0.066)	(0.183)	(0.082)	(0.210)	(0.060)	(0.183)
GDP	0.0123	0.012	0.014***	0.016**	0.015	0.015	0.015**	0.014*
	(0.020)	(0.021)	(0.004)	(0.006)	(0.010)	(0.010)	(0.007)	(0.008)
$Airport\ size$	0.048**	0.046**	0.011	0.016	-0.014	-0.014	-0.007	-0.008
	(0.020)	(0.020)	(0.011)	(0.010)	(0.009)	(0.010)	(0.009)	(0.010)
$Sector\ length$	0.009***	0.009***	0.012***	0.012***	0.012***	0.012***	0.012***	0.012***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$Toll$		-0.010		0.008		0.001		-0.007
		(0.038)		(0.011)		(0.012)		(0.011)
$Fuel$		-0.002		-0.001				
		(0.002)		(0.000)				
$Constant$	5.758***	6.002***	4.730***	4.750***	4.762***	4.756***	4.742***	4.766***
	(0.621)	(0.795)	(0.277)	(0.245)	(0.427)	(0.405)	(0.330)	(0.332)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	605	605	605	605	605	605	605	605
R^2	0.674	0.676	0.464	0.472	0.579	0.579	0.600	0.603

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

Table 7: Effect of $HSR^{Competition}$ on the total km travelled by light vehicles on motorway sectors (sub-sample estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$HSR^{Competition}$	0.414**	0.429**	0.068***	0.064**	0.067**	0.067**	0.059**	0.058**
	(0.153)	(0.171)	(0.021)	(0.023)	(0.026)	(0.026)	(0.026)	(0.027)
$Vehicles$	-1.193***	-1.168***	0.292***	0.212	0.220***	0.216	0.204***	0.292*
	(0.191)	(0.261)	(0.070)	(0.194)	(0.076)	(0.199)	(0.052)	(0.160)
GDP	0.020	0.020	0.014***	0.016***	0.016	0.016	0.015**	0.014*
	(0.021)	(0.022)	(0.004)	(0.005)	(0.010)	(0.010)	(0.008)	(0.008)
$Airport\ size$	0.035**	0.035**	0.024**	0.027***	-0.008	-0.008	-0.001	-0.003
	(0.014)	(0.014)	(0.009)	(0.008)	(0.007)	(0.009)	(0.009)	(0.010)
$Sector\ length$	0.010***	0.010***	0.013***	0.012***	0.012***	0.012***	0.013***	0.013***
	(0.002)	(0.002)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)	(0.004)
$Toll$		-0.003		0.007		0.000		-0.008
		(0.032)		(0.011)		(0.012)		(0.010)
$Fuel$		-0.000		-0.000				
		(0.002)		(0.000)				
$Constant$	5.662***	5.720***	4.689***	4.676***	4.720***	4.718***	4.680***	4.698***
	(0.648)	(0.827)	(0.415)	(0.365)	(0.546)	(0.519)	(0.417)	(0.422)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	612	612	612	612	612	612	612	612
R^2	0.701	0.702	0.451	0.457	0.635	0.635	0.667	0.671

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

hub-and-spoke dynamic is less plausible. Tables 6 and 7 report the sub-sample regressions. Again, limiting the discussion to Model (8), the coefficients associated with $HSR^{Opening}$ and $HSR^{Competition}$ are very close to those of the baseline (0.043 and 0.058, respectively) and still positive and statistically significant. These results lend additional reliability to our previous findings.

5.4. Alternative specifications

Table 8 reports regression results of the most extended specification (i.e., the one that includes the full sets of motorway sector, year, and GDP-by-year fixed effects) with a different composition of the sample and alternative treatment variables. In particular, Models (1) and (2) perform the same baseline analyses but includes in the dataset also the motorway sectors previously excluded, as they seek to show that the sample restriction described in Section 3.1 is not driving our estimates. Indeed, the coefficients associated with $HSR^{Opening}$ and $HSR^{Competition}$ reveal no evidence of a modal shift because they are still positive, although only the former is statistically significant at the 10% level.

Subsequently, Model (3) explores an alternative measure of HSR expansion by using a dummy explanatory variable (rather than a continuous variable) that takes the value of 1 whether at least half of the HS line was opened adjacent to a motorway sector i in year t, and 0 otherwise. Also in this case, the coefficient associated with $Dummy\_HSR^{Opening}$ is consistent with the baseline provided by Table 2 and the same explanation applies.

Finally, an additional issue of interest is to empirically test whether the opening of on-track competition exclusively on HS lines had an impact in reducing motorway traffic. To do so, Model (4) estimates this effect by interacting the main explanatory variables of both Equations 1 and 2. The positive coefficient associated with $HSR^{Opening}$ x $HSR^{Competition}$ shows that competition between the incumbent *Trenitalia* and the new operator NTV on HS lines only did not lead to a modal shift from motorway to HSR services. However, its lack of statistical significance suggests that competition on the HSR network only did not lead to an increase in motorway traffic either. Thus, our first interpretation is that the complementary dynamics between the two transport modes are induced by the HSR expansion rather than competition on HS services (see Section 6 for a more detailed discussion).

Table 8: Effect of HSR expansion and HSR competition on the total km travelled by light vehicles on motorway sectors (estimates of alternative specifications)

	log(Vehicle-Km)			
	(1)	(2)	(3)	(4)
$HSR^{Opening}$	0.035*			
	(0.019)			
$HSR^{Competition}$		0.041		
		(0.032)		
$Dummy\_HSR^{Opening}$			0.033*	
			(0.018)	
$HSR^{Opening}$ x $HSR^{Competition}$				0.058
				(0.039)
$Vehicles$	0.077	0.077	0.156	0.167
	(0.105)	(0.103)	(0.141)	(0.137)
GDP	0.004	0.005	0.006	0.007
	(0.010)	(0.011)	(0.009)	(0.009)
$Airport\ size$	-0.003	0.000	-0.010	-0.004
	(0.009)	(0.008)	(0.007)	(0.007)
$Sector\ length$	0.010***	0.010***	0.011***	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)
$Toll$	0.002	0.002	-0.007	-0.007
	(0.008)	(0.008)	(0.007)	(0.007)
$Constant$	5.144***	5.099***	5.272***	5.213***
	(0.401)	(0.406)	(0.370)	(0.375)
Motorway sector	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
GDP x Year	Yes	Yes	Yes	Yes
Observations	953	953	877	877
R^2	0.447	0.448	0.582	0.587

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

6. Discussion

On the clear understanding that it lies beyond the scope of the current article to draw any general conclusions about HSR programmes, we nevertheless believe that our empirical analysis can provide a number of insights that are, moreover, in line with the findings of studies conducted elsewhere.

Since we have found no evidence of a modal shift from motorway to HSR services, the first insight to be gained is that in terms of modal substitution, modes of transport other than the motorway sector are contributing to the excellent demand performance of the Italian HSR network, as documented by Beria et al. (2018). Indeed, the set of studies reviewed by Givoni and Dobruszkes (2013) show that, in most cases, conventional rail is the main mode of origin for HSR passengers, with air transport in second position. Support for these findings in the Italian scenario is provided by Cascetta et al. (2011), who report that the majority of HS users on the Rome–Naples link were already train users, while the percentages of passengers who used the motorway before the HSR opening were just 7.8% on weekdays, 12.4% on Saturdays, and 14.4% on Sundays. Similarly, Bergantino et al. (2015) and Capozza (2016) shed light on the competitive pressure induced by HSR on airline companies operating on Italy's national routes. Moreover, induced demand could represent a third source of HSR passengers. As Cascetta and Coppola (2014, 2015) stress, the contribution of induced demand to total HSR demand is initially low, but tends to rise gradually following the inauguration of the service.

Closely related to this point, the second insight suggests that HSR might have difficulties in attracting car passengers. Here, if we consider travel time as the main factor explaining the level of modal shift from motorway to HSR services, ultimately it is the door-to-door travel time, as opposed to the station-to-station travel time, that matters for the mode choice decision. In other words, access and egress times to/from HSR stations are other determining factors in the overall journey time (Moyano et al., 2018). It is for this reason that HSR investments need to be accompanied by improvements in both the spread of HSR stations and in their accessibility. Furthermore, Givoni and Dobruszkes (2013) remarked how travel time might not be the key parameter for road users, as travelling by car and coach always present advantages and more flexibility in terms of schedule (Bilotkach et al., 2010), route choice, cost (as group size increases), and luggage.

Then, with the premise that the slightly positive impact of HSR expansion on motorway traffic reported here should be interpreted with caution (as the coefficients of interest are barely significant), the third insight is that HSR may have had a positive effect on the economic activities of the surrounding area, which could have led to an increase in the total number of car journeys on these routes. Indeed, although both transport modes connect the same city-pairs, HSR is concerned more with attracting the *"primary"* traffic between a route's nodes (i.e., the largest cities), while motorways connect the *"secondary"* traffic between all the exits along a route, as the average distance travelled by car is significantly less than the average HSR section length. As such, given those differences in the demand characteristics, the two transport modes may interact in a complementary rather than competitive dynamic.

Finally, the last insight to be gained is that HSR development could lead to an unintended increase in car dependency, because while HSR expansion might attract car passengers, it may, at the same time, undermine conventional rail services. In other words, the reduction in demand for conventional rail services (due to the modal shift toward HSR services) may induce rail operators to cut investments in the conventional network. In turn, this deterioration in conventional rail services, combined with a reduction in their frequency of service, may induce passengers to opt for different modes of transport. For instance, the maturation of the HSR network and the entry of NTV increased the supply of fully high-speed services aimed at reducing travel time between city-pairs. These long-distance services, operated by *Frecciarossa* and *Italo* trains on dedicated tracks only, may have reduced commuting opportunities between intermediate stops, since the accessibility (and cost) of fully high-speed services cannot match that of mixed high-speed or conventional services. As a result, HSR expansion may lead to a reduction in rail connectivity for people living along the routes on which HSR has been implemented, and to an unintended increase in car dependency. This view is also supported by Sánchez-Mateos and Givoni (2012).

As highlighted by De Rus and Nombela (2007) and Beria and Grimaldi (2011), this opens up the debate as to whether the mobility needs of broad metropolitan areas (such as those found in Italy, where medium-sized towns are located at relatively short distances from each other), should rely more on a fully mixed high-speed model that allows interconnections with existing conventional lines rather than on a model that satisfies the "need for speed" of long-haul routes by exploiting dedicated tracks only. It should be borne in mind that a policy that promotes rail use at the expense of the car should carefully analyse the impact of HS on conventional rail services. Hence, improvements also in the conventional infrastructure and in the related services might induce to a real reduction in motorway traffic. These are relationships that shall we seek to understand in future research. Moreover, once freight trains start using the new HS lines, we shall test whether the HSR expansion leads to a modal shift of freight from motorways to HSR services.

7. Conclusions

The development of HSR has transformed modal market shares on the routes on which it has been implemented both by generating new demand and by replacing the demand for other modes of transport.

To date, most previous studies have focused on the inter-modal competition between air and rail and on the intra-modal competition between rail operators, while the literature examining competition between car and rail is scant. However, because the reduction in road traffic (and its negative environmental impact) is one of the key drivers offsetting HSR investments, our study has sought to analyse whether the HSR expansion in Italy has led to a modal shift from its motorways to HSR services.

We have empirically tested, first, whether HSR openings adjacent to some motorway sectors have reduced the total km travelled by light vehicles on these sectors during the period 2001-2017; and, second, whether this reduction has been persistent or even more evident after the opening of on-track competition on some adjacent HS and conventional lines between the incumbent *Trenitalia* and the new operator *NTV*, which entered the HS passenger market in 2012.

In so doing, we carried out a generalized difference-in-differences estimation using a unique 17-year panel dataset. This has enabled us to control for many unobservable confounding factors and to exploit the heterogeneous traffic data within all tolled motorway sectors in a quasi-experimental setting.

Our findings reveal that neither HSR openings nor the opening of on-track competition led to a modal shift from motorway to HSR services, as the two transport modes are non-competing. Conversely, HSR expansion had a slightly positive impact on motorway traffic. Indeed, a 10 percentage points increase in the HSR length leads, on average, to a 0.41% increase in the total km travelled by light vehicles on the adjacent motorway sectors.

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Appendix

Table A: Opening dates of $HSR^{Opening}$ up to 2017

Section	Opening year(s)	Line length (km)	Maximum speed (km/h)	Treated motorway sector
Turin–Salerno axis		**873.5**		
Turin–Novara	February 2006	86.4	300	*A4 Torino–Milano*
Novara–Milan	December 2009	38.6	300	*A4 Torino–Milano*
Milan–Bologna	December 2008	182.0	300	*A1 Milano–Bologna*
Bologna–Florence	December 2009	78.5	300	*A1 Bologna–Firenze*
Florence–Rome	1977-1992	254.0	250	*A1 Firenze–Roma*[a]
Rome–Gricignano	December 2005	186.0	300	*A1 Roma–Napoli* and *A1 Collegamento Firenze–Roma–Napoli*
Gricignano–Naples	December 2009	19.0	300	*A1 Roma–Napoli*
Naples–Salerno	June 2008	29.0	250	*A3 Napoli–Salerno*
Milan–Venice axis		**91.6**		
Milan–Treviglio	June 2007	27.0	200	*A4 Milano–Brescia*
Treviglio–Brescia	December 2016	39.6	300	*A4 Milano–Brescia*
Padua–Venice	March 2007	25.0	220	*A4-A57 Padova–Mestre*
Other lines[b]		**114.0**		
Verona–Bologna	July 2009	114.0	200	*A22 Verona–Modena*

[a] We exclude the *A1 Firenze–Roma* motorway sector from the analysis because the competitive HS section was already in operation since 1992.
[b] Short sectors of the Naples–Bari and Palermo–Messina–Catania lines were upgraded during the second half of 2017; however, precise data are not available.
Sources: Authors' own calculations based on Beria et al. (2018), RFI website, and *Trenitalia*'s financial statements.

Table B: Opening dates of $HSR^{Competition}$ up to 2017

Section	Opening year(s)	Line length (km)	Maximum speed (km/h)	Treated motorway sector
Turin–Salerno axis		**873.5**		
Turin–Milan	December 2012	125.0	300	*A4 Torino–Milano*
Milan–Bologna	April 2012	182.0	300	*A1 Milano–Bologna*
Bologna–Florence	April 2012	78.5	300	*A1 Bologna–Firenze*
Florence–Rome	April 2012	254.0	250	*A1 Firenze–Roma*[a]
Rome–Naples	April 2012	205.0	300	*A1 Roma–Napoli* and *A1 Collegamento Firenze–Roma–Napoli*
Naples–Salerno	August 2012	29.0	250	*A3 Napoli–Salerno*
Milan-Venice axis		**88.0**		
Brescia–Verona	March 2016	63.0	Conventional line	*A4 Brescia–Padova*
Padua–Venice	October 2012	25.0	220	*A4-A57 Padova–Mestre*
Other lines		**441.0**		
Verona–Bologna	December 2015	114.0	200	*A22 Verona–Modena*
Bologna–Padua	October 2012	123.0	Conventional line	*A13 Bologna–Padova*
Bologna–Ancona[b]	December 2013	204.0	Conventional line	*A14 Bologna–Ancona*

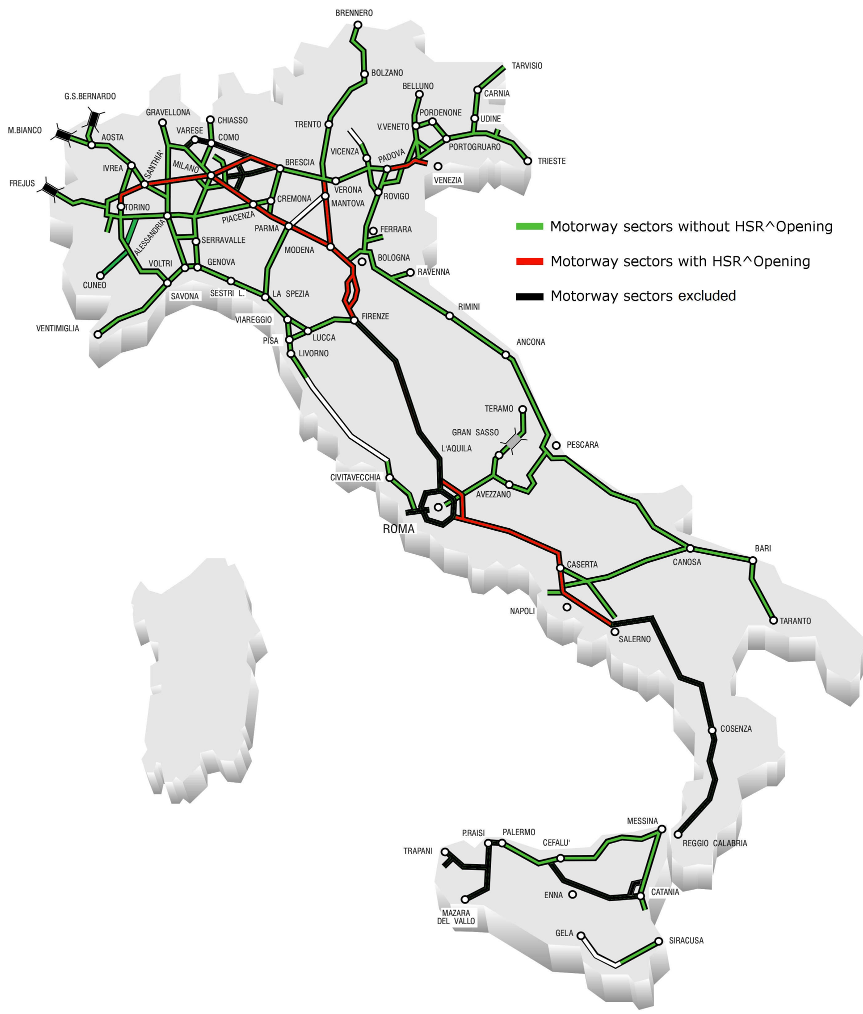
[a] We exclude the *A1 Firenze–Roma* motorway sector from the analysis to make Equation 1 and Equation 2 fully comparable.
[b] On-track competition lasted until December 2014, then *NTV* decided to keep only some seasonal services during summer to serve the holiday destinations (Beria et al., 2016).
Sources: Authors' own calculations based on Bergantino et al. (2015), *NTV* website, and *NTV*'s financial statements.

Table C: Italian tolled motorway sectors up to 2017

Motorway		Motorway	
Code	Sector	Code	Sector
A1	*Milano–Bologna*	*A13*	*Bologna–Padova*
A1	*Bologna–Firenze*	*A14*	*Bologna–Ancona*
A1	*Coll. Firenze–Roma–Napoli*	*A14*	*Raccordo di Ravenna*
A1	*Roma–Napoli*	*A14*	*Ancona–Pescara*
A3	*Napoli–Salerno*	*A14*	*Pescara–Canosa*
A4	*Ivrea–Santhià*	*A14*	*Canosa–Bari–Taranto*
A4	*Torino–Milano*	*A15*	*Parma–La Spezia*
A4	*Milano–Brescia*	*A16*	*Napoli–Canosa*
A4	*Brescia–Padova*	*A18*	*Messina–Catania*
A4-A57	*Padova–Mestre*	*A20*	*Messina–Palermo*
A4	*Venezia–Trieste*	*A21*	*Torino–Piacenza*
A5	*Torino–Ivrea–Quincetto*	*A21*	*Piacenza–Brescia*
A5	*Quincetto–Aosta*	*A22*	*Brennero–Verona*
A5	*Sarre–Traforo del Monte Bianco*	*A22*	*Verona–Modena*
A6	*Torino–Savona*	*A23*	*Udine–Tarvisio*
A7	*Genova–Serravalle*	*A24*	*Roma–Torano*
A7	*Milano–Serravalle*	*A24*	*Torano–Teramo*
A8-A9	*Milano–Varese/Lainate–Chiasso*	*A25*	*Torano–Pescara*
A8-A26	*Diramazione*	*A26*	*Voltri–Alessandria*
A10	*Ventimiglia–Savona*	*A26*	*Alessandria–Gravellona* Toce
A10	*Savona–Genova*	*A27*	*Mestre–Belluno*
A11	*Firenze–Pisa*	*A30*	*Caserta–Nola–Salerno*
A11-A12	*Sestri–Livorno/Viareggio–Lucca*	*A31*	*Valdastico*
A12	*Genova–Sestri*	*A32*	*Torino–Bardonecchia*
A12	*Livorno–Rosignano*	*A33*	*Asti–Cuneo*
A12	*Roma–Civitavecchia*	*A56*	*Tangenziale di Napoli*

Source: Authors' own elaboration based on AISCAT (2017).
Notes: We excluded the motorway sectors described in Section 3.1.

Figure A: $HSR^{Opening}$ expansion in Italy up to 2017



Source: Authors' own elaboration based on AISCAT (2017).

Notes: The excluded motorway sectors are the toll-free sectors managed by ANAS, as explained in Section 2, and the sectors described in Section 3.1. The white motorway sectors are planned or under construction.

Figure B: $HSR^{Competition}$ expansion in Italy up to 2017

Source: Authors' own elaboration based on AISCAT (2017).

Notes: The excluded motorway sectors are the toll-free sectors managed by ANAS, as explained in Section 2, and the sectors described in Section 3.1. The white motorway sectors are planned or under construction.

Table D: Effect of $HSR^{Opening}$ on the total km travelled by light vehicles on motorway sectors (lead and lag estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
3 years before	0.229	0.194	0.047***	0.045***	0.000	0.001	-0.008	-0.008
	(0.246)	(0.232)	(0.011)	(0.012)	(0.009)	(0.009)	(0.009)	(0.009)
2 years before	0.214	0.176	0.068***	0.064***	0.011	0.011	0.002	0.003
	(0.258)	(0.248)	(0.012)	(0.014)	(0.013)	(0.013)	(0.011)	(0.011)
1 year before	0.255	0.213	0.090***	0.088***	0.020	0.020	0.010	0.011
	(0.259)	(0.256)	(0.013)	(0.015)	(0.018)	(0.017)	(0.016)	(0.016)
year of $HSR^{Opening}$	0.275	0.241	0.111***	0.110***	0.020	0.020	0.006	0.006
	(0.260)	(0.259)	(0.014)	(0.016)	(0.016)	(0.016)	(0.015)	(0.015)
1 year after	0.240	0.204	0.104***	0.101***	0.024	0.024	0.006	0.005
	(0.270)	(0.273)	(0.018)	(0.020)	(0.020)	(0.020)	(0.016)	(0.016)
2 years after	0.205	0.159	0.065***	0.068***	0.003	0.003	-0.018	-0.019
	(0.249)	(0.261)	(0.021)	(0.021)	(0.032)	(0.032)	(0.030)	(0.030)
3 years after	0.252	0.236	0.110**	0.111**	0.037	0.038	0.015	0.016
	(0.237)	(0.243)	(0.044)	(0.042)	(0.025)	(0.025)	(0.022)	(0.023)
4 or more years after	0.177	0.214	0.140***	0.137***	0.079*	0.079*	0.061	0.059
	(0.279)	(0.294)	(0.045)	(0.046)	(0.043)	(0.044)	(0.043)	(0.044)
$Vehicles$	-1.211***	-0.925***	0.219**	0.168	0.154*	0.168	0.118	0.166
	(0.229)	(0.274)	(0.092)	(0.135)	(0.081)	(0.130)	(0.076)	(0.137)
GDP	0.014	0.017	0.012***	0.015***	0.015**	0.014	0.011*	0.007
	(0.017)	(0.018)	(0.004)	(0.005)	(0.007)	(0.009)	(0.006)	(0.009)
Airport size	0.060***	0.055***	0.014	0.015	-0.015*	-0.016*	-0.007	-0.007
	(0.017)	(0.017)	(0.011)	(0.011)	(0.008)	(0.008)	(0.008)	(0.008)
Sector length	0.010***	0.010***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$Toll$		-0.043		0.006		-0.002		-0.007
		(0.031)		(0.008)		(0.007)		(0.007)
$Fuel$		0.002		-0.000				
		(0.002)		(0.000)				
$Constant$	5.831***	5.668***	5.040***	4.972***	5.015***	5.045***	5.101***	5.219***
	(0.562)	(0.659)	(0.295)	(0.263)	(0.354)	(0.374)	(0.313)	(0.372)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.649	0.662	0.388	0.392	0.556	0.556	0.583	0.585

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.

Table E: Effect of $HSR^{Competition}$ on the total km travelled by light vehicles on motorway sectors (lead and lag estimates)

	log($Vehicles - Km$)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
3 years before	0.581	0.563*	0.111***	0.123***	-0.003	-0.003	-0.017	-0.017
	(0.345)	(0.332)	(0.027)	(0.025)	(0.026)	(0.026)	(0.027)	(0.027)
2 years before	0.587	0.571	0.136***	0.141***	0.037	0.037	0.025	0.023
	(0.352)	(0.354)	(0.029)	(0.029)	(0.026)	(0.026)	(0.024)	(0.024)
1 year before	0.528	0.491	0.096***	0.093***	0.036	0.036	0.018	0.014
	(0.353)	(0.369)	(0.032)	(0.032)	(0.028)	(0.029)	(0.025)	(0.026)
year of $HSR^{Competition}$	0.462	0.376	0.004	0.008	0.021	0.020	0.006	0.001
	(0.353)	(0.379)	(0.034)	(0.037)	(0.034)	(0.035)	(0.035)	(0.035)
1 year after	0.493	0.442	0.014	0.018	0.019	0.018	0.011	0.003
	(0.360)	(0.382)	(0.036)	(0.037)	(0.039)	(0.041)	(0.043)	(0.045)
2 years after	0.280	0.281	0.028	0.029	0.047	0.046	0.039	0.030
	(0.375)	(0.397)	(0.033)	(0.033)	(0.036)	(0.036)	(0.044)	(0.042)
3 years after	0.364	0.440	0.123*	0.123*	0.085	0.084	0.078	0.068
	(0.396)	(0.408)	(0.065)	(0.065)	(0.066)	(0.069)	(0.073)	(0.074)
4 or more years after	0.451	0.551	0.203***	0.195***	0.112*	0.111	0.105	0.098
	(0.391)	(0.401)	(0.066)	(0.067)	(0.067)	(0.068)	(0.072)	(0.073)
$Vehicles$	-1.214***	-0.924***	0.197*	0.142	0.141	0.149	0.110	0.152
	(0.226)	(0.272)	(0.103)	(0.147)	(0.089)	(0.138)	(0.082)	(0.142)
GDP	0.015	0.017	0.011**	0.017***	0.014**	0.014	0.011*	0.007
	(0.017)	(0.017)	(0.004)	(0.005)	(0.007)	(0.009)	(0.006)	(0.009)
Airport size	0.061***	0.056***	0.017	0.015	-0.016**	-0.016*	-0.008	-0.008
	(0.016)	(0.016)	(0.010)	(0.010)	(0.008)	(0.008)	(0.008)	(0.008)
Sector length	0.010***	0.009***	0.011***	0.011***	0.011***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$Toll$		-0.043		0.006		-0.001		-0.006
		(0.031)		(0.008)		(0.008)		(0.007)
$Fuel$		0.002		0.000				
		(0.002)		(0.000)				
$Constant$	5.813***	5.679***	5.063***	4.897***	5.010***	5.029***	5.096***	5.213***
	(0.553)	(0.652)	(0.315)	(0.292)	(0.367)	(0.392)	(0.325)	(0.389)
Motorway sector	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Year	No	No	No	No	Yes	Yes	Yes	Yes
GDP x Year	No	No	No	No	No	No	Yes	Yes
Observations	877	877	877	877	877	877	877	877
R^2	0.651	0.664	0.384	0.389	0.552	0.552	0.580	0.582

Notes: All specifications present OLS estimates and include motorway sector, year, and GDP-by-year fixed effects as indicated. Standard errors clustered at the highway level are in parentheses. Significance values: ***p<0.01, **p<0.05, *p<0.10.