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High-Speed Rail: A game changer for Spanish motorway transport?☆

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ABSTRACT

Spain has deployed the world's largest High-Speed Rail (HSR) network, in per capita terms, under the premise that this infrastructure provides a cleaner mode for reaching their environmental commitments. However, for observing environmental gains, there should be inter-modal substitution from polluter modes to the HSR. This paper analyzes the impact of new HSR openings on car traffic, using a Generalized and Staggered Difference-in-Difference approach. Unlike previous studies, we analyzes the entire Spanish HSR network. We matched the georeferenced data on car traffic with the origin–destination routes provided by Google Maps API to estimate the impact of the HSR on car traffic. We found that the HSR has not generated modal split, except for few of the HSR segments, in which we estimated a 6%–8% reduction in the annual average daily traffic. These results have public policy implications for the transport policy in the EU, and the effectiveness of decarbonization policies.

1. Introduction

Decarbonizing the transport sector has taken a prominent role in the strategy to combat climate change (ITF, 2019). Since 1996, the European Commission has provided significant financial support to the Trans-European transport network deployment with the aim to ensure the sustainable mobility of persons and goods, while achieving the objectives from the European Union in regard to the environment and competition (Art.2, EU Parliament, 1996). The last has made the High-Speed Rail (HSR) a popular mode of transportation, since not only represents a faster mode at medium-haul distances,[1] but also a less polluting one (without taking into account the construction phase[2]). However, for observing environmental gains, there should be an actual inter-modal substitution from more polluting mode of transportation, as cars,[3] to the HSR.

We analyzed whether the HSR has generated modal substitution from passengers cars in the highways towards the HSR. That is, whether the opening of a particular HSR route between a city-pair, caused a reduction in the number of cars in the highways within the same segment. We took Spain as a case study for the following reasons: (1) After China, Spain is the country with the second largest HSR network in the world, and in per capita terms, the largest in the world, with a HSR network over 3,000 km that sums up to the cost of 56 billion euros by 2019 (AIReF, 2019); (2) Moreover, Spain is the country that has benefited the most from the support provided by the EU for the deployment of this type of infrastructure, getting around 11 billion from the EU up to 2017, which is half of the total funding made available to other EU member states for this type of infrastructure (EU Court of Auditors, 2018); (3) As other cases within the European Union, the decision to build HSR is often based on political considerations, and cost-benefit analyses are not used generally as a tool to support cost-efficient decision-making (EU Court of Auditors, 2018). In the case of Spain, the planning of the HSR routes were not precisely aimed to solve a traffic congestion problem within the highways (Audikana, 2021). In this sense, we can rely our identification strategy on this fact and provide causal estimates for the impact of the HSR on car

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[1] This railway technology allows for maximum speeds of 124 mi/h to 217 mi/h (UIC, 2022)

[2] A growing number of studies has documented the importance of the construction phase in accounting for the life-cycle polluting cost of the HSR. See UIC, 2016 for a discussion on this topic.

[3] According to the International Energy Agency (IEA, 2020), the transport sector contributes globally with 7.3 GtCO2 per year, where 3 GtCO2 per year were produced by the passenger car segment. The above highlights the relevance of the automobile sector in terms of CO2 emissions; however, it underestimates the contribution of other sectors, such as aviation, to climate change, since a greater proportion comes from non-CO2 emissions (Lee et al., 2021).

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Table 1
Modal shares for passenger transport in mainland Spain 2005–2019.

Mode	Unit	2005	2010	2015	2019	Change	Growth contr.
A. Air Total	Mill. Pass-km	29,765	30,449	25,392	35,030	5265	1.35
	Share (%)	7.63	7.67	6.84	8.52	0.90	
b1. Rail Conventional	Mill. Pass-km	19,203	16,320	16,004	16,912	−2291	−0.59
	Share (%)	4.92	4.11	4.31	4.11	−0.81	
b2. Rail High-Speed	Mill. Pass-km	1848	5939	10,027	11,807	9959	2.55
	Share (%)	0.47	1.50	2.70	2.87	2.40	
B. Rail Total	Mill. Pass-km	21,051	22,259	26,030	28,719	7668	1.96
	Share (%)	5.39	5.60	7.01	6.99	1.59	
c1. Cars	Mill. Pass-km	337,797	341,629	317,553	342,005	4208	1.08
	Share (%)	86.56	86.02	85.56	83.21	−3.35	
c2. Motorcycle	Mill. Pass-km	1623	2802	2150	5245	3622	0.93
	Share (%)	0.42	0.71	0.58	1.28	0.86	
C. Road Light-vehicle	Mill. Pass-km	339,420	344,430	319,703	347,251	7831	2.01
	Share (%)	86.98	86.73	86.14	84.49	−2.49	
Total Transport Modes	Mill. Pass-km	390,236	397,139	371,125	410,999	20,763	5.32

Notes: (1) Author's elaboration with data from Observatorio del Transporte y la Logística en España (OTLE) and OFE (2019); (2) Road Heavy-vehicles are not included due to a methodological change that affects the data's comparability; (3) The shares are computed over the number of passengers–vehicles reported.

traffic; (4) Since before 1970, Spain has systematically collected data on public and private highway's traffic, which produce a consistent sample that span a few years before the entry of the first HSR, in 1992, and allow us to implement a difference in difference approach, and; (5) Since an additional 5,654 km of new HSR network is expected to be built in the following years for an estimated value of 73 billion euros (AIReF, 2019), it is important to provide some insights regarding the convenience of this type of transport policy in terms of potential environmental gains that could be generated if a modal substitution from cars to the HSR is actually happening.

Aggregated data on passenger's transport demand for mainland Spain show us that, within the last 15 years, the mode of transport has experienced some notable changes, specifically, indicating an increase in the utilization of the HSR and a decrease in reliance on cars. Since the HSR in Spain is a mode of transport that only serves the passenger segment, the last could lead us to conclude that a potential modal substitution from cars to the HSR is currently underway. In particular, we observed from Table 1 that both, Air Transport (row A) and High-Speed Rail (row b2) have gained noticeable participation in the modal transport market, increasing their market share in 0.90 pp and 2.4 percentage point (pp), respectively, and that altogether, the gains in market share obtained by the Air Transport and the HSR almost accounts for the share of the market lost by the Cars (−3.35 pp); Moreover, the Table 1 also show us that the HSR was the transport mode that captured, in a greater proportion, the total growth in the passenger's transport demand (5.3 pp), contributing on almost half of this growth (2.55 pp). Likewise, Conventional Rail (row b1) has also decreased participation over the same period, probably due to the reduction in its services availability caused for accommodating the HSR service over some of the routes. However, although the HSR has gained participation in the transport modal market, we cannot infer from this table a causal relationship from the entry of the HSR to the decline in cars participation.

In this paper, we assessed the effect of the HSR entry on the passenger's light-vehicle segment in the Spanish highways.[4] For this, we have gathered geo-referenced information on cars traffic for the whole highway's network managed by the National Government and high-priority roads, public and private.[5] In total, the data takes into consideration at least 73% of the whole highway's traffic in the Country (Mapa de Tráfico, 2019). Additionally, we have used *Google Maps API* to retrieve all the available highway routes (origin–destination) that connects a pair of cities where an HSR station is located. In this way, we are able to identify all the available highways routes that competes with a particular HSR segment, as well as their corresponding traffic. Using the year in which the HSR started operation, we implemented a Difference in Difference (DiD) approach, and a staggered DiD approach, following Callaway and Sant'Anna (2021), to identify the effect of the HSR entry on the car's traffic. In particular, our results did not indicate that the entry of the HSR, on average, have caused a modal substitution from cars to the HSR. However, the modal substitution is only observed in very few HSR segments that has the feature of connecting important poles of employments (e.g. Madrid, Barcelona, and Malaga), to medium-sized cities, within one hour of distance using the HSR, though the effect is low, and estimates indicates a reduction between 6%–8% of the Annual Average Daily Traffic (AADT) in those segments.

Most of the recent empirical papers has focused in understand the relationship between HSR and air travel, finding that the entry of the HSR caused a reduction in air traffic (Clewlow et al., 2014; Castillo-Manzano et al., 2015; Zhang et al., 2018; Li et al., 2019), the frequency of flights (Jiménez and Betancor, 2012; Dobruszkes et al., 2014; Zhang et al., 2019a) and the number of seats offered in competing routes (Albalate et al., 2015; Wan et al., 2016).[6] However, the literature analyzing the effects of the HSR on road transport is more scarce, even when both mode of transport competes within a travel distance in which the generalized cost is comparable between them. In this sense, Campos and Gagnepain (2012) proposed a general framework to analyze the full inter-modal effects of the HSR, however, due to lack of information to disentangled the road traffic, they only assessed the effects of the HSR on air travel (low-cost and traditional) within the Paris-Amsterdam route. Moreover, using a discrete choice experiment for two locations in Southern Italy, Bergantino and Madio (2020)

[4] For simplicity, we will refer to this segment as cars, since cars represented over 90% of light-vehicles sample.

[5] In Spain, roads are managed by different levels of governments, National, Autonomous Communities, Province, and Municipalities. The data used in this research considers all the roads managed by the National government, plus those under the following criteria: (1) Roads managed by the Autonomous Communities which are considered as first level priority due to their high traffic density; (2) High-capacity roads (i.e., roads with more than one lane in each side, that are not crossed by other communication routes at level, and which have a higher maximum speed limit than other roads); and (3) Those that, regardless of their category, have an average annual daily traffic (AADT) greater than 8,000 vehicles/day.

[6] For a recent literature review on the relationship HSR-air travel see Zhang et al. (2019b)

studied how individuals change their mode of transportation when the HSR becomes available. Their study provides insights regarding the full inter-modal effects of the HSR, since it considers road, rail, and air travel modes, however, the choice is measured based on a stated preferences survey and it does not represent observed demand or supply figures.

On the other side, empirical papers that analyzes the relationship between HSR and road transport is more scarce. Most of the papers has focused on analyzing the impact of the HSR on a single segment, and in general, have not employed quasi-experimental methods. In the case of studies with information ex-post (Cascetta et al., 2011) surveyed car travelers from the route Rome-Naples in Italy to determine the probability of inter-modal substitution from cars to the HSR, estimating very low values in the cross elasticities of car choice with respect to the HSR, which meant that the HSR hardly affected car use. Moreover, Givoni and Dobruszkes (2013) reviewed different studies that analyzed the inter-modal substitution by different segments (e.g. Madrid-Seville, Rome-Naple, Osaka-Hagata, among others). Comparing the mode share on a route before and after the introduction of HSR services, they accounted that the changes in ridership is about 10%–20% induced demand, and the rest is attributed to mode substitution, although most of the substitution come from the conventional rail and the contribution are modest from other modes as aircraft, car, and coach. As far as we know, the only paper that takes a quasi-experimental approach for the whole HSR network in Italy is (Borsati and Albalate, 2020). In their paper, they analyzing both, the effect of the HSR Opening, and the presence of HSR competition on light-vehicles. They found that HSR Opening did not lead to a modal shift from motorway to HSR services. In our paper, we take a comprehensive approach and analyzes, in a quasi-experimental setting, the causal impact of new HSR routes openings on motorway transport in Spain.

This paper contributes in filling the gap in the literature at analyzing the effect of the HSR on private cars. Our approach differ from previous research in the following ways: (1) Although we recognize that on long-distance trips a main highway provides most of the connection between a city pair, we accounted for the fact that in some cases more than one highway can connect the cities, particularly on mid-distance trips. This is the case of city pairs connected by toll, and toll-free highways. In particular, we retrieved geo-referenced data from Google Maps API that allow us to identify all the different routes that provides a city pair connection, and we assign them their respective traffic count over the geo-referenced position on those routes. As far as we know, we are the first to use this approach on this type of research; (2) We take a comprehensive approach in analyzing the impact of the whole HSR network on cars since its beginnings. The last fills a gap in the literature, since most of the research has been done for a single, or a subset of HSR lines; (3) we acknowledge the limitations of the canonical Difference-in-Difference framework in assessing the Average Treatment on the Treated (ATT) when the treatment is granted on variations in treatment timing. In our case, this variation is caused by the different years in which the HSR started operations. Hence, we provide further evidence using a staggered Difference-in-Difference approach as proposed by Callaway and Sant'Anna (2021); (4) Lastly, we provide evidence using traffic data of the whole State's highways (both, free and toll-highways) which is open and provided by the Spanish government, this differentiate from other studies with similar approach that uses only tolled highways in their analysis (e.g. Borsati and Albalate, 2020).

In the next section, we provide some context to the Spanish case. Then, in Section 3, we provide information about the data we used on this research, as well as some assumptions related to the assigning of the cars traffic into the treatment and control group. In Section 4, we present our empirical strategy followed by the main results. In Section 5, we present some robustness analysis and further results. Finally, Section 6 provides some remarks and conclusions.

2. Context

A few months after the entry of Spain into the European Community, in 1986, the Spanish government took the decision to modernize the country's railway sector after decades of declining competitiveness when we compared it to other modes of transport, such as road and air (which had been increasing their service's routes in the previous years). In a rather unexpected way, the government decided that the way to modernize the railway sector would be launching the first high-speed rail line between Madrid and Seville, on the occasion of the *Universal Exhibition of Seville*, in 1992 (Albalate and Bel, 2014). However, the route chosen by the government had serious inconsistencies from different points of view. First, it was argued that the HSR was an important step for increasing cohesion and transit with other countries of the European Community, however, the Madrid-Seville route, which connects the capital of the country with the south of Spain, would contribute little to none to this goal, since at the time, it was isolated with no other HSR line making the connection to Portugal, nor France. Second, cost-benefit studies have shown that the route had not been chosen either to satisfy the low transportation demand, or the very localized supply deficits, in fact, the HSR represented an over-investment that bore little relation to the traffic data, producing a very low project's rate of return (De Rus and Inglada, 1993; and De Rus and Inglada, 1997).

The absence of economic or social rationality in HSR projects is not unusual across European countries. For instance, the (EU Court of Auditors, 2018) has documented various cases where an HSR line has been constructed despite evaluations of these projects revealing a negative return (e.g., the Rhine – Rhône HSR in France) or even in the absence of cost-benefit studies (e.g., the Halle/Leipzig–Erfurt HSR in Germany). In the same vein, some authors have documented that, in the case of Spain, the deployment of the HSR network is driven more by political considerations than by solving a congestion problem or achieving economic or social benefits. In this sense, Audikana (2021) has documented the different motives that led the Spanish governments[7] to continue deploying HSR lines over the country. Particularly, the motives were related to the idea of accelerating Spain's integration into the European Community, and the guiding principle of connecting all provincial capitals to Madrid. These arguments have been mentioned before by other authors as Bel (2010), and Beria et al. (2018). In particular, they all agree in the fact that in planning the HSR routes, the government put a decisive weight on political arguments rather than on the inter-urban mobility needs, the population in which the HSR stations would be located, or even on whether other existing transport's modes already had been satisfying the transport demand. In fact, the political leverage overcome economic efficiency criteria in the development of the HSR (Betancor et al., 2015). The last is particularly important when we consider that the HSR deployment was the main policy (if not the only one) aimed at modernizing the decay in the railway sector. In figure A1 in the Annex, we can observe the evolution of the total length (in km) of the railway sector by type of use.[8] In particular, we can observe that the railways used for the Conventional

[7] In fact, not only the different national governments played a role in promoting the deployment of HSR, but according to Audikana (2021), the European Union and local political actors played an important role as well. This is evident when we observe that the European Commission has financed around 25% of the total HSR's infrastructure in Spain from 1993 to 2020 (AIReF, 2019), or has destined to Spain almost half of the total co-funding, between 2000 and 2017, granted to all of their EU Member States to this type of infrastructure, even when there has not been a realistic long term plan for high speed rail promoted by the EU (EU Court of Auditors, 2018).

[8] We classify as Conventional Rail those railway gauges of Iberian size, while the HSR is conformed by the UIC standard or mixed gauge railways. The Metric gauge railways are not included, however, they seem to have followed the same pattern as the Conventional Rail.

Table 2
HSR lines by inauguration dates.

Line	Cities connected	Month	Year	Year-mod.	Group
Madrid - Sevilla	ES-M, Cd. Real, Ptollanos, Vill. Córdoba, ES-CO, ES-SE	April	1992	1992	NW1
Madrid - Front. Francesa 1	ES-M, ES-GU, Calatayud, ES-Z, ES-L	October	2003	2004	NW1
Zaragoza - Huesca	ES-Z, Tardienta, ES-HU	December	2003	2004	NW1
Córdoba - Málaga	ES-CO, Puente Genil, Antequera, ES-MA	December	2007	2008	NW1
Madrid - Valladolid	ES-M, ES-SG, ES-VA	December	2007	2008	NW1
Madrid - Front. Francesa 2	ES-L, ES-T, ES-B	February	2008	2008	NW1
A Coruña - Stgo. Comp	ES-C, Santiago de Compostela	December	2009	2010	NW2
Madrid - Valencia	ES-M, ES-CU, Requena, ES-V	December	2010	2011	NW1
Stgo. Comp - Ourense	Santiago de Compostela, ES-OR	December	2011	2012	NW2
Madrid - Front. Francesa 3	ES-B, ES-GI, Figueres	January	2013	2013	NW1
Albacete - Alicante	ES-AB, Vilena, ES-A	June	2013	2013	NW1
Stgo. Comp - Vigo	Santiago de Compostela, Vigo	March	2015	2015	NW2
Valladolid - León	ES-VA, ES-P, ES-LE	September	2015	2016	NW1
Madrid - Toledo	ES-M, ES-TO	November	2015	2016	NW1
Olmedo - Zamora	Olmedo, ES-ZA	December	2015	2016	NW2

Note:
Author's elaboration.
Only cities that are Province's capitals are shown with their ISO 3166-ES name, the other cities with its abbreviated name.
See, https://www.iso.org/obp/ui/es/#iso:code:3166:ES.

Train have been declining since the mid-80's. This reduction can only be explained by the fully depreciation of the infrastructure, which implies a lack of maintenance in this segment of the rail transport. Moreover, we can observe that after 1992, only the rail infrastructure used by the HSR was increased.

An additional feature of the Spanish's HSR is that until recently, the transportation service was only provided by the State Owned Enterprise (RENFE-ADIF). This has serious implications in terms of competitiveness and efficiency. For instance, Hörcher and Tirachini (2021) present a discussion regarding the liberalization of passenger rail services in the EU, and the implications of privatization and the open access competition in the main HSR routes. Furthermore, Álvarez-SanJaime et al. (2015) developed and simulated a model comparing a private against a mixed duopoly regime, using two Spanish's HSR routes (i.e. Madrid-Valencia, and Madrid-Sevilla). They found that the entry of a new rail operator is socially beneficial only when it entails very large increases in rail traffic demand, which improves upon the mixed duopoly regime. Although in our research, the period analyzed only consider a context in which only one provided offered the HSR services (i.e., RENFE-ADIF), it is important to highlights the traffic demand as a determinant of social gains in the deployment of new HSR routes in the future.

In Table 2, we show the different HSR lines operating in Spain and its inauguration dates. In particular, it is noteworthy to observe that the time gap between the first and the second HSR inauguration (i.e., 1992 to 2003) is similar to the time that passed between the opening of the second HSR route and the other 13 new HSR routes (from 2003 to 2015). The last inform us about the speed in which the new HSR lines were deployed in the country. Moreover, we can observe the influence of political forces at the local level in the HSR planning, since some of the cities connected are inconsequential from a transport planing perspective. For instance, in the route Madrid-Sevilla, cities as Ciudad Real, with a total population of 74,000 persons in 2019, Puertollanos, with 47,000 persons, and Villanueva de Córdoba, with 8,700 persons, were connected to the HSR, even when neither of the three cities are within the top 100 most populated cities in Spain. For the purpose of this research, this last feature will be key in estimating the effect of HSR on road passenger cars, since it provides a source of exogeneity in our identification strategy, as we will present in Section 4.

Lastly, it is important to observe that some of the HSR lines started operations way past into the year, in some cases up to the last month of the year. Since we will be working with annual data, in order to have a better representation of the full impact that the HSR caused on the traffic, we modified the year of the inauguration depending on the month in which the HSR started operations. In particular, we assigned to the next year, those HSR routes that started operations after June of the inauguration year (e.g., if the HSR was inaugurated on December 2003, in our analysis, we use 2004 as the inauguration year). This is presented in the column Year-mod. of Table 2. In the last column of the table, we present a variable that represent if the HSR line is grouped within the network of lines 1, or 2. That is, as we can observe in figure A2 in the annex, the HSR deployment have generated two unconnected networks in Spain, one serving most of the territory in Spain (NW1), and the other serving only the northwest region (NW2).[9] The last will be important in defining the road routes that could potentially be affected by the entry of the HSR, as mentioned in Section 3.2

3. Data

In this paper, we are interested in investigate if the entry of the HSR into the transport modal market have had an effect on road passenger cars in Spain. For this aim, we have gathered a geo-referenced panel dataset on passenger cars Annual Average Daily Traffic (AADT). The dataset includes all the traffic counters deployed over the whole highway's network managed by the National Government and the high-priority roads for the period 1988–2019 (i.e., four years before the first HSR line started operations). Furthermore, we have used the year in which the HSR started operations, as well as the geo-referenced dataset requested to Google Maps API to signal those highways that could potentially face competition when the HSR start operating on a particular city pair. Finally, we gather information on time-varying controls related to economic, infrastructure, and geographical conditions. More details in below.

3.1. Traffic data

Our main dataset on traffic comes from the Mapas de Trafico 2019 (MT2019) publication, elaborated by the Ministry of Transport in Spain. In particular, the MT2019 publishes, for each of the traffic counter installed on the highways, one pdf file reporting the AADT by light and heavy vehicles. In some cases, the information from these traffic counters goes back to 1960, which is the year in which the Ministry of Transport started to count the traffic in a systematic, and periodic way. For the purpose of this research, we are interested in

[9] The connection between Zamora and Ourense was inaugurated in 2021, making it possible to travel from Madrid to Galicia on a single high-speed network. However, during the period analyzed by this paper (1988–2019), this connection was not yet in service.

traffic counters containing information since 1988. This date has been chosen as a starting point in our analysis for two reasons, first, it is very difficult to find information on control variables at the local level for years before this date; and second, we consider that since this date the number of traffic counters were enough to have a proper representation on the AADT (for instance, we have found that almost half of the traffic counters that exist in 2019 were already installed in the highways by 1988). The information on AADT were later matched with the geo-referenced information of the position of each traffic counter over a particular road, obtaining the geographical distribution of traffic over the highway's network.

In figure A3 in the annex, we show the geographical distribution of the traffic counters over the analyzed period. It is important to mention that although there is no attrition of traffic counters once they have been installed, we can still observed new traffic counters being installed at any moment after 1988 (which is the case, since the number of traffic counters increased from 1521 in 1988 to 3395 in 2019). The last is problematic in those cases where the traffic counter, which is part of the same HSR inter-city route, has been installed after the HSR became operational, since we will not be able to identify the effect of the HSR on road passenger cars. To overcome this, we kept only those traffic counter observations that were installed before the HSR started operations. In Section 4.1, we will show that the dropped counters is low, and it will depend on the inter-city assumption used for identifying the number of highways that could potentially be affected by the inauguration of the HSR (see Section 3.2). Another possibility is that the new traffic counters were installed in highways recently built that connects the same inter-city HSR route. This will not represent a problem if the highway was inaugurated before the HSR started operations in that route. However, for those cases in which this is not true, dropping the counter's observations will also provide a solution.

3.2. HSR openings

We are aimed to investigate if the entry of the HSR into the transport modal market have had an effect on passenger car traffic, we first need to identify those highways that could potentially be affected by the entry of the HSR. Since we are working with data at the traffic counter level, we used their geo-referenced position and matched them with the geo-reference data retrieved from Google Maps API on origin–destination routes. In particular, we constructed a binary variable that is equal to one for those traffic counters that lays over a highways that could potentially be affected by the entry of the HSR since its year of inauguration, and zero otherwise. In this fashion, the traffic counter observations can be grouped in two, a control group formed by those traffic counters that lays over a highways that do not compete with the HSR, and a treatment group formed by those traffic counters that lays over a highways that could potentially be affected by the entry of the HSR. In this context, our binary variable $HSROp$ should be understood as the one aimed at determining the extensive margin of the HSR on highway car traffic. While we acknowledge that this variable aggregates the effects of the HSR-Motorways competition, and that a variable such as time savings between the HSR and cars could help us disentangle whether time savings play a key role in driving modal substitution (as documented for the HSR-Air competition), we are unable to include it in our analysis due to a lack of historical information on travel times for both modes of transportation.

There are some considerations to take into account when we retrieved information from Google Maps API. In particular, when we define the origin–destination of the trip, we follow three different approaches: (1) we identify the highways that provides connection to the same cities within the same HSR line (as defined in Table 2) from one HSR station (origin) to the next one (destination), we called this the One-Ahead approach (or OA); (2) we identify the highways that provides connection to the same pair of cities within the same HSR line (as defined in Table 2), from one HSR station (origin) to any other station (destination), we called this the Multiple-Ahead approach (or MA); (3) we identify the highways that provides connection to the same cities across different HSR lines, but within the same network (as defined in Table 2), from one HSR station (origin) to any other station (destination). A representation of the OA, MA, and NW approaches are in figures A4, A5, and A6, in the Annex.

The implications from the different approaches are not trivial, since each approach provide us with different number of traffic counters within the treatment and control group. The last is due to the fact that for some connections, the fastest route between cities is not the one parallel to the HSR, which is an implication that follows from the OA approach and that has been implicitly used it in previous research as in Borsati and Albalate (2020). For instance, we present in Fig. 1 how the number of traffic counters within the treatment and control group increases as we go from the OA approach to the NW approach. This is something we expect, since we are relaxing our origin–destination assumption to allow for a broader classification of highways that could potentially be affected by the entry of the HSR.

3.3. Control variables

We gathered data at different aggregation levels for economic, social, infrastructure, and geographical conditions. For instance, at the traffic counter level, we extracted from the Mapas de Trafico 2019 information on the number of lanes in a particular segment of the road, the elevation over the sea level (in meters), and whether a traffic counter lays over a tolled highway; at the provincial level, we have gathered information on the Gross Domestic Product from the National Institute of Statistics (INE) and its historical archives. Since there is no concatenated series for the period 1988–2019, we construct it by concatenating the series backwards by their variation rates from year t to t-1. This is especially useful in generating values for the first analyzed years, since the figures were still reported in pesetas (then the local currency of Spain), and not in euros. Furthermore, we use the GDP Deflator reported by the International Monetary Fund to convert the serie to 2015 constant euros. We also gathered information on the stock of passenger's vehicles on each province from the annual yearbook of the Ministry of Interior for the period 1989–2019, and we complemented this information with the data from 1988 reported in the magazine Trafico *y* Seguridad Vial, published by the Ministry of Interior, which reports the number of new car registrations for each of the provinces in each month of the year. Hence, we discount the monthly new registrations from the 1989 figure to get a 1988 stock number. At the Autonomous Community level, we collected the price of the diesel oil from the regional statistic archives of the INE.

4. Empirical strategy and main results

In this paper, we are interested in investigate if the entry of the HSR have had an effect on other modes of transport, in particular, road passenger car. For this purpose, we use a two-way fixed effect approach for estimating the average treatment effect on the treated (ATT) that new HSR lines will have, over the road passenger car segment, on the competing highways. Our empirical specification is detailed in Eq. (1) below, and it will provide us with our baseline estimates of the ATT:

$$\begin{aligned} AADT_{ipt} =& \beta_0 + \beta_1 HSROp_{ipt} + \beta_2 GDPAll\ pc_{pt} + \beta_3 GDPAll\ pc^2_{pt} + \beta_4 StockCars_{pt} + \\ & \beta_5 PGas_{ct} + \beta_6 DToll_{ipt} + \beta_7 NoCarr_{ipt} + \beta_8 Altit_{ipt} + \\ & \gamma_p + \gamma_m + \gamma_h + \gamma_t + \epsilon_{ipt} \end{aligned} \tag{1}$$

where $AADT_{ipt}$ is the Annual Average Daily Traffic for road passenger car in the traffic counter i, within the province p, in the year t. The variable $HSROp_{ipt}$ is a binary variable that takes the value of 1 on those traffic counters located on highways that are potentially affected for the entry of the HSR, according to the approach followed (i.e. OA, MA, NW), from the date of the HSR inauguration on (i.e. on the

(a) One-Ahead: n-Treated = 478 / n-Control = 2700

(b) Multiple-Ahead: n-Treated = 773 / n-Control = 2345

(c) Network: n-Treated = 1622 / n-Control = 1386

Fig. 1. Treatment and Control Group by OA, MA, NW approaches in 2019.

years $t \geq t_{HSR-Inaug}$, in which $t_{HSR-Inaug}$ is defined as Year-mod in Table 2. While HSR_{ipt} is equal to zero otherwise (i.e. when the traffic counter is in a highways that never competes with the HSR, or on the years previous the HSR inauguration). In this sense, we are investigating on the extensive margin that the HSR have on traffic cars in the highway. We also control for time-varying variables as $GDPAll\ pc_{pt}$, which is a variable constructed as the sum of the GDP percapita of the Province (i.e. $GDPProv\ pc_{pt}$) and the GDP percapita from the neighboring provinces (i.e. $GDPNeigh\ pc_{pt}$), and it represents a measure of the income in the region. In our empirical specification, we aim to capture the linear and non-linear impact of the income on traffic volume, and we expect the coefficient β_2 to be positive, and β_3 negative, indicating that increases in income produce an increase in traffic, but at a decreasing rate, respectively (Graham and Glaister, 2004; Goodwin et al., 2004; Graham and Glaister, 2005). We also control for the evolution in the stock of cars registered in a province, $StockCars_{pt}$, and we expect that coefficient β_4 to be positive, indicating that an increase in car ownership produce and increase in traffic (González and Marrero, 2012). We proxied the evolution of the gasoline prices by the evolution of the average diesel gas prices on each of the autonomous community,[10] where c index represents the autonomous community, and is referred by the variable $PGas_{ct}$. Several literature surveys have indicated that the fuel elasticity on road traffic is very heterogeneous but negative (Graham and Glaister, 2004; Goodwin et al., 2004; Dunkerley et al., 2014), indicating that increases in the price of the fuel produce a decrease in the traffic. Furthermore, we created a binary variable that is equal to 1 if the traffic counter is located in a tolled-highway, $DToll_{ipt}$. In this sense, we expect that those roads in which exist a toll will host less traffic, hence, the expected sign of the coefficient β_6 should be negative (Batarce et al., 2023). The variable $NoCarr_{ipt}$ accounts for the number of lanes available in the traffic counter segment, and is aimed to control for extension of lanes in the highways that can have an impact on the traffic of vehicles. We expect that an increase in the number of lanes produce an increase in the traffic (Cervero, 2002). The variable $Altit_{ipt}$ represent the average altitude (above the sea level, in meters) of the province in which the traffic counter is located. In particular, geographical conditions on the

[10] In mainland Spain, 6 out of 15 autonomous communities are formed by only one Province, and the rest of autonomous communities are formed by more than one Province.

Table 3
Descriptive statistics by route approach (OA, MA, NW).

Variables	Treated			Control			Mean diff.	
	nobs	mean	sd	nobs	mean	sd	t-test	p-value
OA approach								
AADT	12 592	19.57	25.71	62 605	10.25	15.00	55.28	0.00
HSROp	12 592	0.45	0.50	62 605	0.00	0.00	225.19	0.00
DToll	12 592	0.15	0.36	62 605	0.05	0.21	42.36	0.00
NoCarr	12 592	3.42	1.48	62 605	2.83	1.17	49.22	0.00
Altit	12 592	512.05	348.56	62 605	512.73	358.98	−0.19	1.15
GDPProvpc	12 592	21.14	4.94	62 605	19.78	4.54	30.21	0.00
GDPNeighpc	12 592	21.80	4.95	62 605	20.61	4.47	26.76	0.00
GDPAllpc	12 592	22.43	5.04	62 605	20.77	4.59	36.41	0.00
StockCars	12 592	599.61	870.05	62 605	340.65	504.67	45.55	0.00
PGas	12 592	87.82	31.84	62 605	89.35	31.77	−4.93	2.00
MA approach								
AADT	20 320	15.56	22.28	53 024	10.35	15.35	35.99	0.00
HSROp	20 320	0.50	0.50	53 024	0.00	0.00	230.27	0.00
DToll	20 320	0.11	0.31	53 024	0.05	0.21	30.07	0.00
NoCarr	20 320	3.23	1.38	53 024	2.78	1.16	44.53	0.00
Altit	20 320	554.74	348.44	53 024	497.77	362.44	19.25	0.00
GDPProvpc	20 320	20.47	4.84	53 024	19.85	4.52	16.30	0.00
GDPNeighpc	20 320	21.69	5.04	53 024	20.51	4.35	31.42	0.00
GDPAllpc	20 320	22.11	5.10	53 024	20.66	4.48	37.71	0.00
StockCars	20 320	486.41	757.47	53 024	336.71	485.78	31.61	0.00
PGas	20 320	87.06	31.91	53 024	89.24	31.81	−8.30	2.00
NW approach								
AADT	40 524	12.58	19.31	31 641	10.73	15.30	13.96	0.00
HSROp	40 524	0.43	0.50	31 641	0.00	0.00	152.98	0.00
DToll	40 524	0.09	0.29	31 641	0.03	0.16	33.08	0.00
NoCarr	40 524	3.03	1.29	31 641	2.72	1.16	33.47	0.00
Altit	40 524	578.60	352.78	31 641	430.96	353.25	55.75	0.00
GDPProvpc	40 524	20.37	4.80	31 641	19.45	4.25	26.85	0.00
GDPNeighpc	40 524	21.36	4.81	31 641	20.14	4.18	35.78	0.00
GDPAllpc	40 524	21.72	4.93	31 641	20.14	4.21	45.51	0.00
StockCars	40 524	412.55	684.96	31 641	321.31	344.45	21.65	0.00
PGas	40 524	87.37	31.86	31 641	89.19	31.84	−7.62	2.00

highways control for urban density and the traffic flow that it can produce on inter-city traffic. We expect the coefficient β_8 to be negative, indicating that more challenging geographies, represented by higher altitude places will be associated with less urban density and thus produce less traffic in the highways (Garcia-López et al., 2015). Lastly, the variables $(\gamma_p, \gamma_m, \gamma_h)$ are fixed effects (FE) at the province, municipal, and highway level in which the traffic counters are located, and allow us to control for all the time-invariant characteristics of those variables. Meanwhile, γ_t is a time FE that controls for common trends that affected all the traffic counters over the years.

The main threat to the identification of the parameter of interest, β_1, is the potential endogeneity between the non-random allocation of $HSROp$, and the variable $AADT$. This would be the case if the HSR routes had been planned to solve a traffic problem that could affect the AADDT variable. However, we have mentioned in Section 2 that this is partially alleviated since the choice of HSR routes occurred in a context where political motivations, rather than economic reasons (or traffic), influenced the result. The last identification strategy is also used by Cobos and Escribano (2022) when analyzed the effects of the HSR on the population density and unemployment rate in Spain's municipalities, and by Albalate et al. (2017) when analyzed the effects of the introduction of HSR services on local tourism.

4.1. Descriptive statistics

In Table 3, we present the descriptive statistics of the variables of interest according to the approach used, and their classification within the control and treatment group. The first thing to notice is how the sample size of the units within the treatment group increases as we go from the OA approach to the NW approach. As we had previously warned, this is due to the fact that when generating the road routes that compete against the HSR, the NW approach represents a broader set of road possibilities than the OA or MA approaches. Furthermore, we can see that the sample size is not the same across the approaches. For example, in the OA approach the total sample size is 75,197 observations (17% in the treatment group), it is 73,344 observations in the MA approach (28% within the treatment group), and 72,165 observations in the NW approach (56% within the treatment group). This is because at the time of moving from the control to the treatment group, the traffic counters that were installed after the HSR inauguration were removed, since they were not useful in identifying the effect of the HSR on the road passenger car.

The second feature to note in the data is that the traffic counters record a relatively higher AADT in the treatment group, compared to the control group. The smallest difference is in the NW approach, with an AADT of 12.6 thousand vehicles per day in the treatment group, and 10.7 thousand vehicles per day in the control group. Moreover, following the OA approach, we can see that out of the sample within the treatment group, 45% records a post-treatment year (HSROp), 15% of the traffic counters are located on a tolled highway (DToll), the average number of lanes in this type of roads are 3.4 (NoCarr), the average elevation (above the sea level) of the province in which the traffic counter is located is 512 meters (Altit), the average GDP per capita of the Province is 21 thousand euros (GDPProvpc), the average stock of cars in the provinces is 599 thousand cars (StockCars), and the average price of gas on the autonomous communities is 88 cents of euro per liter (PGas). We present in the last two columns of the Table 3, the t-test and p-value of a test of mean differences. We noticed that across the different approaches (OA, MA, NW), all the mean differences are significant at the 1% with exception of the variable Altit in the OA approach, and the PGas, in all the approaches.

4.2. Parallel trend

Although the treatment and control group displays significant differences in traffic (AADT) and other local features, in order to interpret

Table 4
Baseline Two-way FE model with OA approach.

	Dependent variable:		
	AADT		
	M1	M2	M3
HSROp	−0.065 (0.523)	−0.061 (0.522)	−0.070 (0.522)
GDPAllpc	0.100 (0.278)	0.079 (0.276)	0.079 (0.276)
GDPAllpc2	−0.004 (0.005)	−0.003 (0.005)	−0.003 (0.005)
StockCars	0.017*** (0.002)	0.017*** (0.002)	0.017*** (0.002)
Pgas		0.038 (0.033)	0.038 (0.033)
DToll			−6.392 (12.147)
NoCarr	5.981*** (0.925)	5.980*** (0.925)	6.034*** (0.933)
Altit	−0.011*** (0.004)	−0.011*** (0.004)	−0.011*** (0.004)
Observations	75,197	75,197	75,197
R^2	0.886	0.886	0.886
Adjusted R^2	0.882	0.882	0.882
Residual Std. Error	6.045 (df = 72541)	6.045 (df = 72540)	6.044 (df = 72539)

Note: *p<0.1; **p<0.05; ***p<0.01.

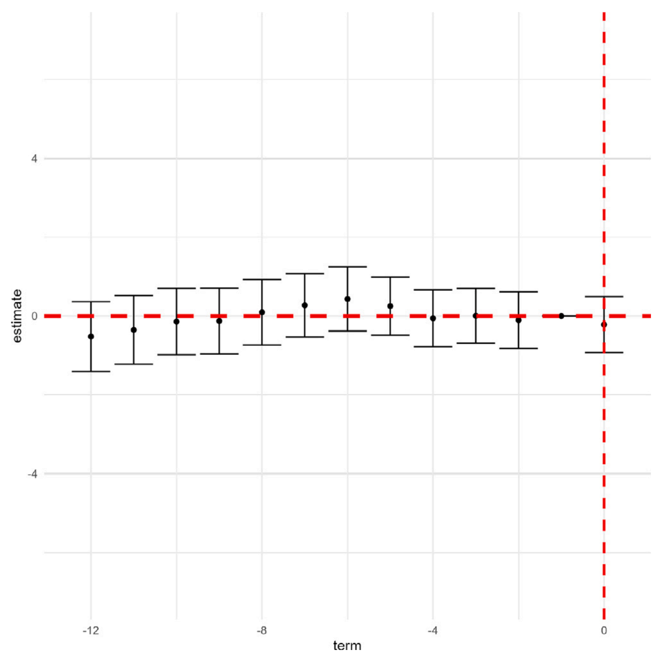

Fig. 2. OA approach - Pretrend Parallel Trend Assumption (Fully Dynamic Event Study)).

the parameter β_1 (in Eq. (1)) as the causal effect of the entry of the HSR on road passenger car, we need to show that the trends between the control and treatment group is parallel in the pre-treatment periods. For this, we will estimate a fully dynamic event study version of Eq. (1). In Fig. 2 we present the estimates for the OA approach, the estimates for the MA and NW approach are presented in the figures A7 and A8, in the annex. Since the first HSR line has only 4 pre-treatment periods, we can confirm that the parallel trend assumption holds for the whole HSR lines sample. In fact, the parallel trend assumption holds for each of the pre-treatment periods individually for up to 13 years before the HSR segment of the remaining lines opened.

4.3. Two-way fixed effects

We show the Two-way Fixed Effects estimates in Table 4 using the OA approach. The estimates for the MA and NW approach are reported in tables A1 and A2 in the Annex. The first thing to take into account is that the negative sign in the parameter of interest implies that the HSR effectively generated an intermodal substitution with cars. This sign is consistent with other empirical specifications, but it is not significant,

Table 5
ATT by approach and control group matching.

Control group	Approach	ATT	Std. Error	95% Conf. Int.	
Never Treated	OA	0.7027	0.8041	−0.8733	2.2787
	MA	0.3218	0.4377	−0.5361	1.1797
	NW	0.2073	0.2969	−0.3747	0.7893
Not Yet Treated	OA	0.6761	0.7936	−0.8794	2.2315
	MA	0.293	0.4401	−0.5696	1.1557
	NW	0.1976	0.2915	−0.3737	0.7689

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

so we cannot differentiate this effect from zero. We also see from tables A1 and A2, that the approach do not affect the results, although it reduces the effect, and in the case of the NW approach, swipe the sign of the coefficient, however, in all cases, the coefficient remains statistically not different from zero.

In term of the control variables, we can say that the GDP per capita of the province and its neighborhoods is positively and decreasingly correlated with AADT, which is what we expected, but again, statistically not different from zero. The stock of cars in a Province is positively correlated to the AADT, however, its effect is very small, although statistically significant. Neither the price of the gas, nor the existence of tolls in the highway have a statistically significant correlation with the AADT. However, the number of lanes on the highway has a positive, and statistically significant correlation. Finally, the altitude where the traffic counter is located has a negative, and statistically significant correlation with the AADT.

4.4. Difference in difference with staggered treatment adoption

In this section we show the estimates of our empirical specification using the methodology proposed by Callaway and Sant'Anna (2021). This methodology allows us to correct for potential bias in our estimates due to the wrong comparison between treatment and earlier treated group, which is the result of the different timing treatment that in our case is represented by the different HSR inauguration years. In this scenario, the Generalized Difference in Difference methodology tends to bias the magnitude of the coefficient of interest. Furthermore, this methodology will also allow us to improve the treatment and control group matching, since it weights the observations through a propensity score formed with the time-varying variables. Moreover, the methodology will allow us to explore heterogeneity in the ATT estimates, which is something that the Generalized Difference in Difference methodology does not allow us. In our case, this is particularly important, since we are interested in estimate both, the aggregated effect of the HSR on cars, as well as the disaggregated effect that a particular HSR cohort of lines have on the intercity route of cars.

Table 6
ATT by approach, cohort, and control group matching.

Never treated				Not yet treated		
Cohort	OA	MA	NW	OA	MA	NW
1992	2.8781	1.1739	1.073	2.8369	1.1241	0.9932
2004	−0.7232	−0.3317	−0.6289	−0.7421	−0.3457	−0.7048
2008	***−1.8809****	***−1.3871****	−0.1318	***−1.8953****	**−1.3852****	−0.0282
2010	−2.7693	−2.7693		−2.9433	−2.9433	−1.6067
2011	−0.1907	−0.1497	−0.0044	−0.1888	−0.1449	0.0209
2012	−0.2655	−0.2627	−1.2609	−0.2284	−0.2129	−0.9983
2013	0.5302	1.0636	0.8462	0.5348	1.0691	0.8454
2015	1.2632	1.3448	1.1747	1.2637	1.3453	1.1726
2016	0.5188	0.328	−0.0123	0.5188	0.328	−0.0123

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

The results for the ATT effect for the OA, MA, NW approach is presented in the Table 5. As can be seen, once that we correct for the potential bias on the ATT produced by the different treatment timing, we found that the parameter is still statistically not different from zero, although now the sign of the coefficient is positive. We can also see that no matter which control group is used to compare the treatment units, that is, the never treated units or the not yet treated units, none of this make an effect in changing the previous results. The previous result confirms that despite the existence of notable differences between the control and treatment groups, which were shown in the descriptive statistics section, the result does not vary even if we compare the effect with units that have not yet been treated, which should constitute a more homogeneous group. In this sense, this results confirm us that at the aggregate level, the HSR network, on average, has not had an effect on modal substitution among cars.

Subsequently, we disaggregated the ATT by the cohort year, that is, by the year in which the HSR line was inaugurated, and in the same way, we proceeded to carry out the disaggregation by the approach used (OA, MA, NW), and the control group used (never treated and not yet treated). As we can see in Table 6, the only HSR line that presents a jointly statistically significant effect is the HSR line that was inaugurated in 2008 (shown in bold and italic numbers), which includes the routes: Cordoba-Malaga (from the Madrid-Malaga corridor), Madrid-Valladolid, and Barcelona-Lleida (i.e., Madrid-Front. Francesa 2, or Madrid-Barcelona corridor, in Table 2). In particular, the observed effect is negative, therefore, we can affirm that an intermodal substitution effect was shown on these routes between the HSR line and the road passenger cars on those inter-city routes. The detailed results are shown in tables A3 - A8 in the annex. In particular, the size of the coefficient tell us that the entry of the HSR caused a reduction on the AADT in around 1.3 and 1.8 thousand vehicles per day, which represent 6%–8% of the AADT of the cohort (i.e. the AADT from the HSR lines inaugurated in 2008) observed four years before the entry of the HSR, according to Table 10, depending the approach used.

Since the only results that are jointly statistically significant at the cohort level are the HSR lines which started operations in 2008, we provide in Fig. 3 its dynamic ATT estimates when compared to never treated and not yet treated control groups for the OA, MA, and NW approach. The dynamic ATT estimates for the other cohorts are included in the Annex A9 – A15. In particular, it is noteworthy to mention that in the OA approach, a small negative effect that is individually statistically significant is obtained until approximately 10 years after the HSR started operations, but only at the 90% of confidence, which could be suggesting a long period of time in which this type of technology is truly adopted as a means of transportation in substitution of the cars. Moreover, it seems that the HSR also have a small and temporal effect on modal substitution in the HSR line that connects A Coruña (a medium-size city which is capital of the provincial government) with Santiago de Compostela (a small city which is the capital of the autonomous community government). As we can see in the Annex A11, the reduction in cars happened between one and two years after the HSR started operations in 2010, however the effect dissipated over the next three years.

5. Robustness

5.1. Urban areas exclusion

In this section we show the ATT estimates once we exclude from the sample those traffic counters that are located on highways segments that are part of a Greater Metropolitan Area (GMA), according to the classification provided by the Spanish's Institute of Statistics (see figure A16 and table A9 in the Annex). In particular, we took out of our sample the top 10 municipalities in terms of population, within a particular Province. As we can observed from table A9, the last allow us to exclude at least 60% of the total population within the GMA. In fact, the principal city within a GMA accumulates 65% of the GMA's population, on average (with some exceptions as Zamora, in which 92% of the total GMA's population is located, and Barcelona as the city that accumulates less GMA's population within a GMA, with 31%). The last is intended to reduce the noise that can be caused by road traffic in highways that occurs in large cities due to short-haul commuting. In this sense, we try to capture only the traffic that is most likely to do an inter-city trip due to reasons not related with short-haul commuting. In Table 7, we present the ATT estimates for the effect of the whole HSR network on cars for the OA, MA, and NW approach, and different control groups, using the staggered difference in difference proposed by Callaway and Sant'Anna (2021). The results confirm our previous findings, that is, on average, the HSR network has not produced a modal substitution with cars. In fact, we also observe that our estimates are pretty close to the ones shown in Table 5, so we can deduce that our results are not lead by the urban traffic produced in big cities.

Likewise, in Table 8 we provide evidence that the HSR segments that actually generated a modal substitution effect are the ones that started operations in 2008. As in the previous section, the estimates are robust to the exclusion of urban areas at the cohort level. In the Annex A17 we presented the dynamic ATT estimates, and we can observe that the pattern shown in Fig. 3 holds, which confirm our previous results.

5.2. Are time savings different between HSR line's cohorts?

One of the main advantage of the HSR is that it provides a faster mode of transport on medium-haul trips, granting HSR a competitive advantage compared with other mode of transport in this segment of the market, as cars, and conventional trains. In particular, as individuals try to minimize the generalized cost of traveling, they will tend to compare which of the different transport modes allow them to save more time within a particular trip. Hence, it is reasonable to expect that

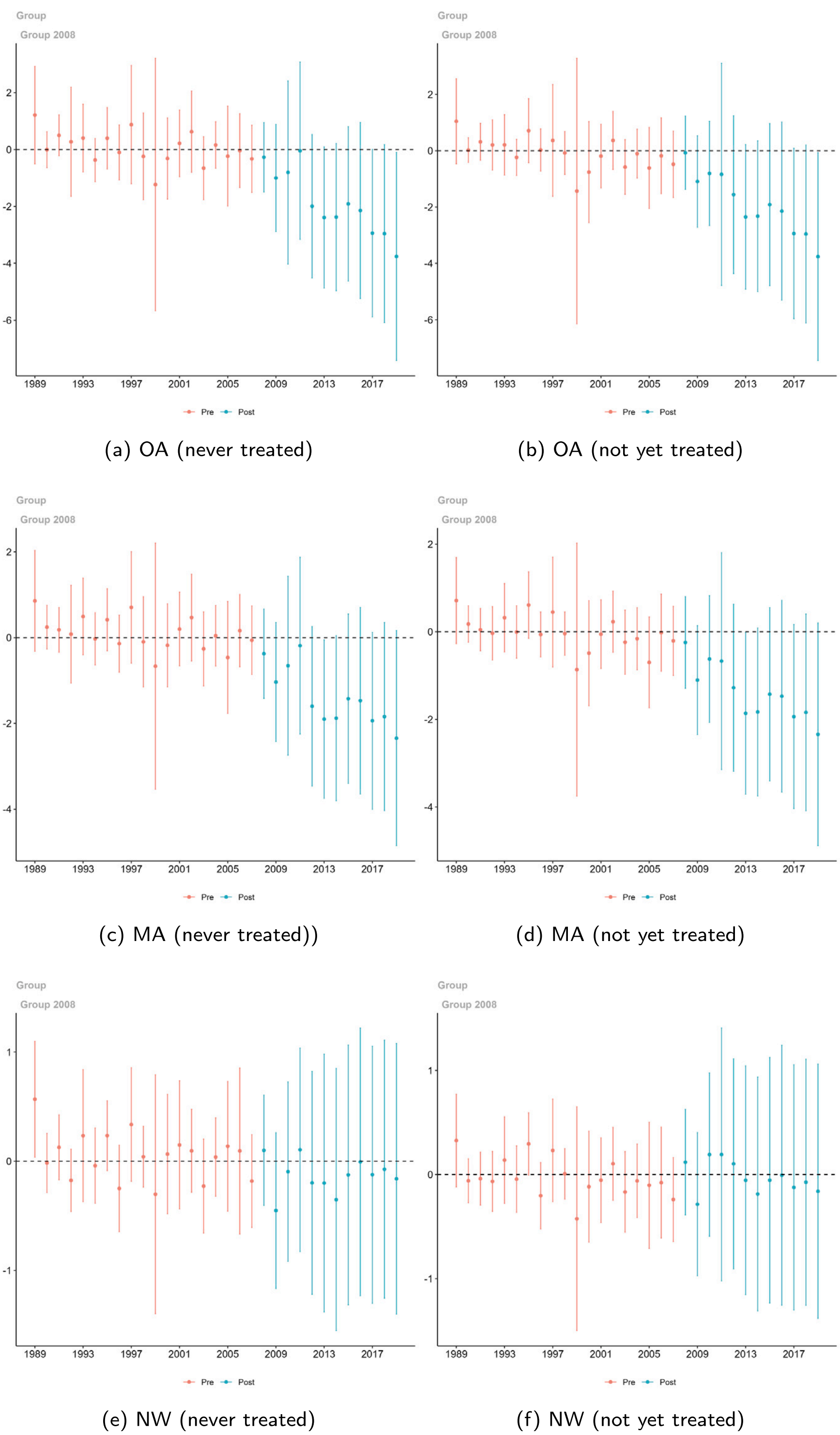

Fig. 3. Dynamic ATT for the 2008 cohort by approach and control group.

on those segments in which the HSR is particularly faster than the cars, then a modal substitution between cars and HSR is likely to happens.

In this section, we try to understand if our results are driven by the speed of the HSR in a particular segment. That is, whether the HSR segments that started operations in 2008 were relatively faster than the other HSR segment cohorts. For this, we gathered information published by RENFE (the State's operator) regarding the average duration of the trip from each segment within a HSR line, following a One-Ahead (OA) approach, as defined in Section 3.2. Moreover, we also used the information provided by Google Maps API to compute the average road trip's duration in regard to the different OA route options. The results comparing the trip's duration by car versus HSR is detailed on table A10. However, in Table 9, we show that traveling a particular segment in car is on average 2.3 times higher than traveling the same segment in HSR.

From Table 9, we observe heterogeneity in time savings computed for different HSR segments (cohorts). Specifically, the segment Zaragoza-Huesca produces the lowest time savings, with only 29%

Table 7
ATT by approach and control group matching excluding urban areas.

Control group	Approach	ATT	Std. Error	95% Conf. Int.	
Never Treated	OA	0.6157	0.9316	−1.2102	2.4416
	MA	0.2756	0.4399	−0.5867	1.1378
	NW	0.1491	0.2761	−0.3921	0.6903
Never Treated	OA	0.6092	0.9393	−1.2319	2.4503
	MA	0.25	0.4335	−0.5996	1.0996
	NW	0.149	0.272	−0.384	0.6821

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

compared to car travel, while the Olmedo-Zamora segment achieves the highest time savings, at 69%. Grouping the segments based on time savings, we find that five HSR segments save less than 50% of travel time, three segments save between 50%–59%, and seven segments save 60% or more. The segments in which we observed modal substitution (i.e., Córdoba – Málaga, Madrid – Valladolid, and Madrid - Front. Francesa 2) are within the group that experience the highest time savings. However, while time savings is an important determinant of modal choice, this table alone does not allow us to conclude that it is the primary driver of modal substitution. In other words, although a subgroup of the HSR segment with the highest time savings experiences modal substitution, other determinants likely contributed to why other HSR segments within this group did not. This highlights the complexity of the relationship between the factors driving modal substitution.

5.3. Does the HSR density matter?

Observing high levels of traffic is a necessary, although insufficient condition for modal substitution, and it is a key parameter for determine if a new transport infrastructure is profitable from a cost–benefit analysis perspective. Several studies has pinpointed that the lack of sufficient demand made most of the Spanish HSR corridors unprofitable or not economically justified (e.g., Albalate and Bel, 2011, De Rus, 2011, De Rus and Inglada, 1997, and Betancor et al., 2015).

In Table 10, we shows for each of the HSR segments, what was the average AADT from competing highways in the previous 4-years before the HSR was inaugurated. In particular, we computed two averages, in column 4, we present the average AADT for the highways that directly compete with the HSR segments that were inaugurated in a particular year (or cohort). Then, using the same years (defined in column 3 as Pre Years), in column 5, we compute the average of all the highways that compete with the HSR network according the OA approach (see figure A4). We compute the ratio from these two average in column 6, which try to represent whether in the years previous the inauguration of a particular HSR segment, the levels of AADT from this segments were above or below the AADT levels from all the highways that were (or will be) competing with the HSR network in some point.

In this sense, it is interesting to observe that 8 out of 14 HSR lines showed a ratio below one, which means that within the 4-years previous the HSR line opening, there were other routes, within the HSR network, that carried more highway traffic in the years analyzed. For instance, the route Madrid-Sevilla carried on average 30% less AADT in the 4-years before its inauguration (i.e. 1992) than the rest of the highways that competes with the HSR network within the same years. Moreover, we can see that the HSR cohort of 2008, conformed by the HSR routes, Córdoba - Málaga, Madrid-Front. Francesa 2, and Madrid - Valladolid, were all with a ratio above 1, which imply that the observed levels of AADT in the highways that competed with the HSR routes were above the total AADT generated in the highways that competes with the whole HSR network in 29%, 52%, and 84% respectively. We can also observe other HSR routes (and cohorts) in which the ratio is above one, but with the temporal individual effect found in the HSR cohort in 2010 (i.e. A Coruña - Stgo. Comp), we have not found any statistically significant effect, or modal substitution, in our econometric

Table 8
ATT by approach, cohort, and control group matching excluding urban areas.

	Never treated			Not yet treated		
Cohort	OA	MA	NW	OA	MA	NW
1992	2.4031	0.9678	0.8608	2.3870	0.9334	0.8180
2004	−0.5511	−0.1901	−0.6863	−0.6312	−0.2533	−0.7310
2008	***−1.6611*****	***−1.2886*****	0.0520	***−1.5907*****	***−1.2521*****	0.1257
2011	−0.3110	−0.2502	−0.0064	−0.3099	−0.2483	0.0128
2012	−0.1517	−0.1520	−0.4031	−0.1518	−0.1415	−0.3317
2013	0.1653	0.2399	0.1850	0.1656	0.2418	0.1809
2015			0.1792			0.1788
2016	0.2908	0.1248	−0.1424	0.2908	0.1248	−0.1424

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

Table 9
Time saving between HSR and Car on different HSR line segments.

HSR line segments	HSR's time savings (% Car trip)	Ratio trip dur. (Car/HSR), avg.	Ratio trip dur. (Car/HSR), cum.
Madrid Sevilla	63%	2.76	2.68
Madrid - Front. Francesa 1	62%	2.66	2.66
Zaragoza - Huesca	29%	1.45	1.41
Córdoba - Málaga	60%	2.49	2.48
Madrid - Valladolid	64%	2.78	2.75
Madrid - Front. Francesa 2	61%	2.59	2.59
A Coruña - Stgo. Comp	46%	1.86	1.86
Madrid - Valencia	58%	2.50	2.37
Stgo. Comp - Ourense	57%	2.32	2.32
Madrid - Front. Francesa 3	59%	2.60	2.41
Albacete - Alicante	63%	2.84	2.84
Stgo. Comp - Vigo	33%	1.49	1.49
Valladolid - León	49%	1.93	1.95
Madrid-Toledo	42%	1.72	1.72
Olmedo - Zamora	69%	3.21	3.21

Table 10
Pre-inauguration traffic density in the HSR lines (4-year average).

Line	Inaug	Pre years	Pre AADT Line	Pre AADT HSR	Ratio
Madrid-Sevilla	1992	1988–1989–1990–1991	8700.67	11 719.61	0.70
Madrid - Front. Francesa 1	2004	2000–2001–2002–2003	14 376.59	19 912.75	0.69
Zaragoza - Huesca	2004	2000–2001–2002–2003	11 660.82	19 912.75	0.56
Córdoba - Málaga	2008	2004–2005–2006–2007	30 838.68	22 652.39	1.29
Madrid - Front. Francesa 2	2008	2004–2005–2006–2007	36 576.28	22 652.39	1.52
Madrid - Valladolid	2008	2004–2005–2006–2007	44 222.65	22 652.39	1.84
A Coruña - Stgo. Comp	2010	2006–2007–2008–2009	41 628.71	23 405.18	1.79
Madrid - Valencia	2011	2007–2008–2009–2010	15 834.17	23 315.25	0.71
Stgo. Comp - Ourense	2012	2008–2009–2010–2011	14 036.70	22 849.11	0.63
Albacete - Alicante	2013	2009–2010–2011–2012	12 526.83	22 207.30	0.60
Madrid - Front. Francesa 3	2013	2009–2010–2011–2012	36 893.14	22 207.30	1.75
Stgo. Comp - Vigo	2015	2011–2012–2013–2014	22 381.32	21 080.77	1.08
Olmedo - Zamora	2016	2012–2013–2014–2015	11 051.01	20 859.33	0.52
Valladolid - León	2016	2012–2013–2014–2015	10 573.73	20 859.33	0.50

Author's elaboration.

analysis (e.g. Madrid - Front. Francesa 3, and Stgo. Comp - Vigo), which confirm our initial argument that density is a necessary, although insufficient condition for modal substitution.

6. Conclusions

Spain has prioritized high-speed infrastructure like no other country in the European Union, making it the country with the most kilometers built per capita in the world. For this, it has relied on extensive resources provided by the taxpayers of the European Community, whose objective is the development of sustainable transport aimed to contribute in the environmental commitments acquired by the EU. However, for this policy to work an actual substitution from polluter to cleaner mode of transport must be observed.

Our study shows that in aggregate terms the HSR has not generated this intermodal substitution, however, when we analyzed the evidence by HSR cohort, we can verify intermodal substitution in a couple of HSR lines, which reduce their AADT between 6%–8%, on average. This effect is individually statistically significant only up to several years after their inauguration (around 10 years), which can be signaling a delayed adoption of this type of transportation. While we have observed minimal to no modal substitution between the HSR and highway cars, it is reasonable to anticipate that, as traffic demand rises, the HSR can increasingly accommodate this growth, thereby restraining the escalation in other transportation modes like road or air travel. The drivers that could be behind on how HSR accommodates traffic growth is deferred to future research.

A peculiar feature that distinguish the HSR lines in which we observed a modal substitution is that they connect relatively large cities, such as Madrid, Barcelona, and Malaga, with medium-sized cities such as Valladolid, Lleida, and Cordoba. This results could potentially be understood if this type of modal substitution is led by passengers who commute between those connected cities, although this needs to be tested in further research. In this regard, some research has documented that the dominant reason people travel by HSR is business (Dobruszkes et al., 2022). The latter highlights an important issue that is outside the scope of this research but adds to the implications that this type of infrastructure can produce on spatial equity and HSR modal choice. In particular, some research has documented that the use of this type of infrastructure is prevented by economic and geographic considerations. That is, the HSR could be serving a segment of the market that do not perceive exclusion due to the high HSR fares, or the access/egress time to HSR stations, which tend to be located in the city center, thus increasing the time cost for rural or out-of-the city population. This opens a debate about the use of taxpayers' money in this type of infrastructure that does not benefit the entire population equitably (Pagliara and Biggiero, 2017; Pagliara et al., 2016; and Biggiero et al., 2017).

Additionally, we have shown that the observed modal substitution is not correlated with the speed of the HSR (or the time savings with respect to the cars), and we presented descriptive evidence that suggest that a high density in the highways that compete with the HSR route in the 4-years before its opening, is a necessary, although insufficient condition to observe modal substitution, which highlights the complexity of the relationship between the factors driving modal substitution.

The last set of results have public policy implications. First, the amount of money that has been invested in deploying this type of infrastructure is surely not compensated for the null or little modal substitution observed, which make us hesitate about the effectiveness of this policy to reduce carbon emissions; Second, we presented descriptive evidence that showed that a higher AADT in the years previous the HSR opening is partially correlated with the likelihood to observe modal substitution in a HSR route, which make us wonder if the new planned HSR routes (for an additional 73 billion euros), that compete against highways with smaller AADT, makes sense from the modal substitution point of view; Lastly, although it has been shown that transport improvements can have positive wider economic impacts (Graham and Gibbons, 2019), and more specifically that the HSR can have short and long term impacts on productivity and economic activity (Blanquart and Koning, 2017, Vickerman, 2018), it seems that for the case of Spain, investing in HSR with the aim to reduce CO_2 emissions through modal substitution, is not a good idea, since the traffic density in some of the HSR segments are very low, and hence, it would be very unlikely to observe modal substitution in the current institutional setup. For future research, it would be interesting to document whether the recent entry of competitors to offer HSR services generates an increase in their demand, so that it is more likely to observe modal substitution.

CRediT authorship contribution statement

Daniel Albalate: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing. **Carlos R. León-Gómez:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ecotra.2024.100360.

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