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Received: 17 May 2021 | Revised: 24 December 2021 | Accepted: 8 January 2022

DOI: 10.1111/jors.12583

RESEARCH ARTICLE

JOURNAL OF REGIONAL SCIENCE WILEY

Roads to innovation: Evidence from Italy

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Abstract

In this study, we leverage on the ancient Roman roads network as a source of exogenous variation to identify the causal effect of the modern highways network on innovative performance of Italian NUTS-3 regions. Empirical findings suggest that a 10% increase in the highways stock in a region generates an increase in the number of patents of about 3%–4%, over a 5-year period. Further analysis suggests that our findings can in part be explained by a reduction in travel costs that fosters collaborations among inventors living in different regions and by an increase in the degree of centrality in the regional innovation network associated to denser highways networks. Finally, we find that the innovation-enhancing effect of highways declines over time, possibly because of the introduction of information and communication technology, or the increasing congestion on the Italian network.

KEYWORDS

highway network, innovation, knowledge accumulation, knowledge spillover, regional development, road infrastructure, roman road network

1 | INTRODUCTION

The role of transport infrastructure investments in fostering growth has been extensively studied in the economics and regional science literature. As documented by recent surveys, like Ferrari et al. (2019), and meta-analysis, like Melo et al. (2013), transport infrastructures have been found to display significant impacts on different economic

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outcomes. A reduction in transport costs associated to transport infrastructure investments can generate higher productivity of other inputs and lower production costs, can increase trade and competition by enlarging relevant markets and can favor the exploitation of scale economies. Furthermore, greater accessibility contributes to raise the market potential of different locations, thus affecting the spatial allocation of human capital and economic activities (agglomeration economies). Another channel through which transportation infrastructures can have important economic effects is the fostering of knowledge creation and diffusion process.[1] By lowering transportation costs, transport infrastructure may indeed make the interactions among inventors easier. This in turn tends to increase the spread of (localized) knowledge across space.

Hence, it becomes crucial to understand if transport infrastructure investments, among other possible policy tools, are able to stimulate the innovation and knowledge spillovers that are often constrained by geography (Jaffe et al., 1993). However, with very few notable exceptions (e.g., Agrawal et al., 2017), this issue has been substantially neglected by previous literature.

This study investigates the impact of road infrastructures (motorways) on the innovative capacity of Italian (NUTS-3) regions and explores possible transmission mechanisms.[2] In particular, we exploit cross-sectional variation at regional level to evaluate whether larger highway networks tend to make the spatial diffusion of knowledge easier, which in turn tends to foster innovative activity. To give a causal interpretation to our results, we need to address a difficult identification issue linked to possible simultaneity between regional technological evolution and transport infrastructure investments. Indeed, such investments are typically not randomly allocated whenever governments tend to build infrastructures in low-income and low-innovation regions, or when high growth driven by local innovation fosters the demand for mobility and therefore the construction of highways. Moreover, there might be omitted factors that drive both infrastructures and innovation. To tackle this issue, we follow the historical route instrumental variable (IV) approach suggested by the urban and regional economics literature (Redding & Turner, 2015) and pioneered by Duranton and Turner (2012). This approach grounds on the idea that the presence of a transport network built in the past can be a good predictor for successive infrastructure investments.[3]

In this study, we consider the ancient Roman roads dating back to 117 AD as an instrument for the modern motorway endowment of the Italian regions.[4] Following the literature, we argue that the Roman road network is reasonably exogenous, given that Roman roads were built mainly for military purposes; therefore, conditionally on a rich set of geographic controls, we assume that there are not important local unobservables, that explain both the construction of Roman roads in certain areas and their (very) long run patterns of growth.

Following Agrawal et al. (2017) we estimate our model for the year 1988, which precedes the large diffusion of the information and communication technology (ICT) and we let regional innovation performance depend on the motorways stock lagged 5 years. Indeed, the ICT revolution might have boosted or reduced the impact of road infrastructures on innovative activity, depending on the substitutability or the complementarity between personal interactions and ICT in the knowledge production process.

Our first main result is that the stock of highways has a positive and significant impact on regional innovative activity. Estimates suggest that an increase of 10% in the length of the motorways network leads to an increase of about 3%–4% in regional innovation as measured by forward citation weighted sum of patents. These findings are confirmed when we use unweighted patent counts and when we consider patents by region and technological sectors as observation units; moreover, they are robust to the inclusion of a set of geographical, innovation, and historical control variables and to the use of an alternative measure of innovative capacity based on the address of

[1]More recent endogenous growth theory models rest on knowledge spillovers as one of the most important engines of growth (Acemoglu & Akcigit, 2012; Akcigit et al., 2016).

[2]In this study, the terms “region” and “NUTS-3 region” will be used interchangeably to indicate the Italian NUTS-3 statistical territorial unit.

[3]Studies that have followed this approach include Duranton et al. (2014), Agrawal et al. (2017), and Baum-Snow et al. (2017), among others.

[4]Such instruments have been firstly adopted by Garcia-López et al. (2015) when studying the impact of highways on the sub-urbanization of Spanish cities and have been successively employed in different studies like Percoco (2015), Holl (2016), De la Roca and Puga (2017), De Benedictis et al. (2018), and Garcia-López (2019).

the applicants instead of the inventors' place of residence. Finally, we uncover evidence of important heterogeneous treatment effects, as we find that roads favor innovation particularly in certain patent technology sectors and in those regions where inventors are more scattered over the territory: this is exactly what we should find if we believe that roads foster innovation by making communication easier within a region.

Moreover, we add to the literature by investigating possible transmission channels that may explain the link between highways and regional innovative performance. Indeed, overall results can be associated to different transmission mechanisms, such as those related to agglomeration economies, working through the attraction of human capital, the enlargement of the relevant market, and the diffusion of knowledge across space. In particular, we focus on the process of knowledge creation and diffusion, both within regions and across neighboring ones and we offer novel evidence supporting the importance of improved knowledge flows.

First, we analyze whether higher cross-regional connections facilitate collaborations among inventors located in different regions by estimating a gravity model of ideas. Results show that the number of collaborations tend to be higher in those region-pairs that have denser highway networks. This finding suggests that highways might tend to increase innovation (also) by spreading knowledge diffusion between regions, and not only within regions, as found by Agrawal et al. (2017).

We then explore inventors' collaboration patterns by following a social network analysis (SNA) approach, as the structure of research collaborations can be viewed as a network composed of links and nodes (Galaso & Kovářík, 2021). In particular, we investigate whether highways regional endowment favors regional embeddedness into a wider interregional innovation network, as proxied by different measures of node centrality (e.g., Wanzenböck et al., 2014). Indeed, node centrality within a collaboration network has been found to exert a positive impact on regional innovation, by increasing knowledge flows and absorptive capacity of knowledge spillovers (Ahuja, 2000; Burt, 2000; Owen-Smith & Powell, 2004; Whittington et al., 2009). By considering a simple network of co-patenting, where NUTS-3 regions are nodes, this is the first work that studies the role played by highways in enhancing regional embeddedness. IVs estimates suggest that conditional on a set of innovation, geographical, and historical controls, highways tend to enhance various indicators of regional centrality (e.g., Degree, Betweenness, Eigenvector) within the network of collaborations.

Another extension of our analysis is devoted to study the temporal pattern of the impact of highways network on regional innovation and finds that such effect has declined over time. This result can be associated to the diffusion of ICTs or to congestion effects generated by the large increase in traffic that occurred over the sample period.

Finally, in some empirical specifications, we find weak evidence of displacement effects. Such result would be in line with the hypothesis of a spatial reorganization process of economic activity taking place, so that the increase of innovative activity in one region takes place, at least in part, at the expense of nearby ones (Redding & Turner, 2015). However, the lack of robustness across specifications precludes us from giving too much weight to this result.

This study is organized as follows: Section 2 describes the related literature and delineates the novel contribution of this study; Section 3 presents our database, and in Section 4, we describe the identification strategy. Empirical results are discussed in Section 5 which is followed by the conclusions.

2 | RELATED LITERATURE

This study is related to different strands of literature. First, it fits to the wide and rapidly expanding literature on the effects of roads infrastructure on regional growth and productivity.[5] Within this context, Fernald (1999) is perhaps one of the first studies offering a convincing identification strategy that exploits industry differentials of sensitivity

[5]For a recent survey that focuses on studies employing counterfactual impact evaluation methods, see Redding and Turner (2015). Ferrari et al. (2019) provide an up-to-date review of the economic effects of transport infrastructure for each transport mode.

to transport costs: industries relying relatively more on road services should be particularly affected by improvements in the road network. By applying a variant of the Difference-in-Differences (*DiD*) identification strategy to a set of US industries over time, he finds that regional TFP growth was positively affected by the construction of the US highways system. Another important study which in turn pioneered the historical route identification approach is Duranton and Turner (2012), who find that an increase in the stock of highways within the US metropolitan statistical areas (MSAs) leads to an increase in employment of about 1.5% after 20 years. Moreover, the authors suggest that their result is unlikely to simply reflect the spatial reorganization of economic activity. A recent paper by Ghani et al. (2016) evaluates the impact on productivity, employment, output, and number of establishments of the so-called Golden Quadrilateral (GQ) project, a recent major investment program which involved a massive upgrade of the GQ highways network in India. The authors finds that such investments significantly affected the growth of manufacturing activity, the number of firms, and labor productivity.[6]

A more specialized literature this paper contributes to has focused on the impact of highways and railways on innovation. In the seminal work by Agrawal et al. (2017), the authors analyze the impact of interstate US highways on regional innovation. They apply an IV approach to deal with possible endogeneity of highway endowment and find that a 10% increase in interstate highways leads to a 1.7% increase in regional patenting activity over a 5-year period. In particular, they suggest that roads facilitate knowledge creation and diffusion also by favoring knowledge flows within metropolitan statistical areas; in particular, they show that the average distance between the location of a given patent and the patents it cites from the same region, is larger in MSAs with denser highways networks. Following Agrawal et al. (2017), Wang et al. (2018) use an IV approach to examine the impact of road development on local innovation in China. In particular, to overcome endogeneity issues associated to roads endowment, they use city mean slope as an estimation instrument, arguing that the mean slope can be considered a proxy for the relative cost of road construction. The authors suggest that a 10% improvement in road density increases the average number of approved patents per company of 0.71%. Turning to railways, Yamasaki (2017) analyses the effect of rail access on the adoption of steam energy by analyzing the expansion of the Japanese rail network between the late 1800s and early 1900s. Using a *DiD* identification design together with an IV approach, the author suggests that the growth of rail access from 1888 to 1892 accounts for 67% of the growth of steam energy observed over the period 1888–1902.[7] Lin (2017) estimates a DiD model on a panel of Chinese cities observed over the period 2003–2013 to assess the impact of high-speed rail (HSR) on a number of economic outcomes, including patent applications, as a proxy for innovation activities within a city. Among other results, the authors find that HSRs stimulate innovation by favoring greater scientific collaboration between cities and diffusion of knowledge. In turn, in Dong et al. (2020), the relation between knowledge diffusion and the construction of China's HSR is analyzed for the period 2006–2015. By instrumenting the construction of HSR with the Chinese railroad network in 1962 and the geographic slope for cities, the authors show that, in Chinese cities connected to the HSR network, researchers experienced a significant increase in productivity, both in terms of quantity and quality of scientific publications.[8] Lastly, Andersson et al. (2020) apply a *DiD* design to identify the impact of railway connections on Swedish municipality innovative capacity in late XIX century. The authors report a positive impact of railways connection on innovation, as well as an increase in patent transfers between inventors and firms.[9]

Finally, our study is related to the issue of promoting innovation at regional level. Starting with the seminal work of Jaffe et al. (1993), knowledge accumulation tends to be considered geographically localized. Indeed,

[6]Another interesting study on the impact of the massive investments in highways in China is the one by Xu and Nakajima (2017), who find a positive effect of highways construction on investment and output, with notable differences across types of regions and industries.

[7]The authors construct their instrument by calculating the “cost-minimizing route” between destinations using slope information to account for costs of construction.

[8]See also Inoue et al. (2017), who use a *DiD* strategy to identify the effect of the opening the Nagano–Hokuriku Shinkansen HSR on firm level innovation in Japan.

[9]See also the recent study by Ejermo et al. (2021), who show that, after the construction of the motorways and railways Öresund Bridge between Malmö and Copenhagen, patents per capita increased in the Malmö region.

innovation is fostered by several common features of the local "milieu," like clusters of high-tech firms, presence of research centers, and by any other characteristic that may favor knowledge spillovers. Moreover, innovation benefits from local interfirm alliances, mutual information, and interactions between firms, scientists, and specialized suppliers. Such relations promote knowledge flows and learning processes, thus allowing knowledge exchanges of both formal and informal nature. Therefore, agglomeration processes favor the transmission of tacit knowledge, that can support the emergence of more stable and longer research joint projects (Bennett et al., 2000; Hervas-Oliver & Albors-Garrigos, 2008; Love & Roper, 2001). In particular, agglomeration is likely to reduce search costs, uncertainty, and transaction costs associated to joint projects, so that firms can exploit the benefits of increasing returns from collaboration (Abramovsky & Simpson, 2011).[10]

Our study contributes to the above-mentioned strands of literature in at least four number of ways. First, it is the first paper that analyzes the impact of road infrastructure on regional innovation performance using data for an EU country; in fact, to the best of our knowledge, empirical evidence on this issue has never been provided other than for the United States or China. Second, our study is based on units of observations (NUTS-3 data) that significantly differ from the US MSAs considered in Agrawal et al. (2017) along various dimensions. Italian NUTS-3 regions, unlike the US MSAs, always share borders with each other and are very heterogeneous in terms of economic development; as far as population is concerned, the average Italian region in our sample tend to be significantly smaller than the average US MSA, with the distribution of the US MSAs significantly more skewed. Finally, Italian NUTS-3 region covers the entire national population, unlike in the case of the US MSA.[11] Such characteristics allow us to better analyze the issue of spillover effects of transport investments on nearby regions at a quite narrow level of spatial aggregation. Third, while Agrawal et al. (2017) report evidence of knowledge flows within regions, our results suggest that more developed highways networks are associated to higher collaborations across regions. Last but not least, this is the first study that analyzes a previously neglected transmission mechanism, namely that a denser highways network can affect regional innovative capacity by fostering the region's degree of centrality within the national innovation network.

3 | DATA

Our study analyzes the relation between roads and innovation, as measured by per capita weighted patent fractional counts, for 89 Italian NUTS-3 regions as defined in 1974.[12] In particular, we primarily rely on fractional patent counts weighted for forward citations as a measure for innovation output.[13] Indeed, the economic literature recognizes patents as fundamental instruments of appropriation of the innovative activity; moreover, technologies with greater impact on welfare and economic development are more likely to be patented (Pakes & Griliches, 1980). In particular, the innovation literature (Pakes & Griliches, 1980) has identified forward citations as an indirect measure of the invention value, as the number of citations received by a patent reflects its importance in the development of subsequent technologies (Hall et al., 2005; Trajtenberg, 1990). However, patents measure inventions but do not measure all innovative activity (Smith, 2005) and not all inventions are patented. Nevertheless,

[10]It is worth noting that New Economic Geography (NEG) literature proposes some theoretical models where location choices and growth are jointly determined (see, among others, Baldwin & Martin, 2004; Black & Henderson, 1999; Fujita & Thisse, 2002; Minerva & Ottaviano, 2009).

[11]As far as the Chinese case is concerned, the analysis has been conducted at the prefecture-city level, which tends to be significantly larger than Italian NUTS-3 regions, as can be seen from the descriptive statistics shown in Lin (2017).

[12]Despite the number of Italian NUTS-3 regions has recently increased, we consider the 1974 local administrative setting that counts 95 NUTS-3 regions: this is because information on motorways kilometers in 1983 is available only for the 1974 setting. Moreover, we drop from the sample six regions that do not have highways (Brindisi, Matera, Agrigento, Ragusa, Siracusa, and Grosseto) so that our sample includes 89 regions. Indeed, dropped regions are equipped with road infrastructure similar to motorways, which however are not easily measurable for our sample period.

[13]The geographical distribution of patent applications is assigned according to the "inventor criterion," that is, according to the inventor place of residence. If a patent has more than one inventor, the patent application is distributed equally between all of them and consequently between their NUTS-3 regions of residence.

as argued by the innovation literature, patents are an effective measure of local technological capacity. We recover annual data on patents from the European Patent Office (EPO) repository (*EPO–Patstat*) that includes bibliographical and legal status patent data on several countries at NUTS-3 regions level. Patent data refer to patent applications filed directly under the European Patent Convention or to patent applications filed under the Patent Co-operation Treaty and designating the EPO (Euro-PCT). A detailed set of information on applications, like the number of forward citations, applicants and inventors and their characteristics, the relative technological International Patent Classification (IPC) class of the patent, and NACE-2 statistical classification of economic activity are included.[14] We recover patent data for the period 1978–2015 and we “regionalize” raw patent information by means of inventors' address (NUTS-3 codes). Data are finally classified according to different technological sectors, following the WIPO systematic technology classification, based on the codes of the IPC. In particular, we identify five patent classes, namely Electrical Engineering, Instruments, Chemistry, Mechanical Engineering, and a fifth class including residual ones. Data are collected until 2015 since the 2 last years of available data underestimate application counts because of the delays in the publication of patent data (18/24 months since application).[15] Figure 1 (panel a) shows the territorial distribution of weighted patents in 1988.

Turning to roads infrastructure regional endowment, we consider the total number of kilometers of motorways in each NUTS-3 region as provided by the Italian Central Institute of Statistics and the Automobile Club of Italy.[16] Figure 1 (panel b) shows the length of motorways in the Italian peninsula in 1983. As far as data on the length of Roman roads is concerned, in particular, for those defined as major/consular roads, we rely on the Digital Atlas of Roman and Medieval Civilization (DARMC), which provides georeferenced data at the regional (NUT-3) level on the road network of the Roman Empire in 117 AD and we calculate the length of the major Roman roads in each Italian NUTS-3 region.[17] Figure 1 (panel c) shows the resulting map; in particular, in the Italian peninsula, the total length of major roads is almost 10,000 km.[18]

Following Duranton and Turner (2012) and Agrawal et al. (2017), we include in the analysis a complete set of geographical control variables, like (NUTS-3) regions surface, the difference between maximum and minimum altitude, and an index of terrain ruggedness.[19]

As for historical controls, which proxy for the degree or historical urbanization and for the level of economic development, we rely on data provided by Guiso et al. (2016). In particular, we recover information on the size of cities in 1300s and we find out how many cities in each NUTS-3 region had a population exceeding 1000 people. We then construct a dummy variable that takes the value 1 if a region has a number of cities with these demographic characteristics above the national average value, and 0 otherwise. In addition, we also include a dummy that takes value 1 if in each NUTS-3 region there was at least one city with a Bishop seat before 1000 CE. Table 1 reports basic descriptive statistics for the main variables used in the study.

4 | IDENTIFICATION STRATEGY

Following Agrawal et al. (2017), we consider a model where the innovative activity in each Italian region in 1988 is a function of the length of the motorways' system in 1983:

$$lnInnov_{i,88} = \alpha + \beta(lnMotorways_{i,83}) + \gamma(lnInnov_{i,83}) + \varphi X_i + \upsilon_i. \quad (1)$$

[14]WIPO IPC-based technology field classification. Source: WIPO IPC Technology Concordance Table.

[15]See Bronzini and Piselli (2016) for more details.

[16]See https://ebiblio.istat.it/SebinaOpac/resource/statistica-degli-incidenti-stradali/IST0010868

[17]The main predecessor of this database is Talbert (2000) which provides maps of the entire Greek and Roman Empires, covering the territory of over 75 modern countries.

[18]Our calculation of the length of major Roman roads in each Italian NUTS-3 region is consistent with that of Licio (2020).

[19]Authors' elaboration from Nunn and Puga (2012).

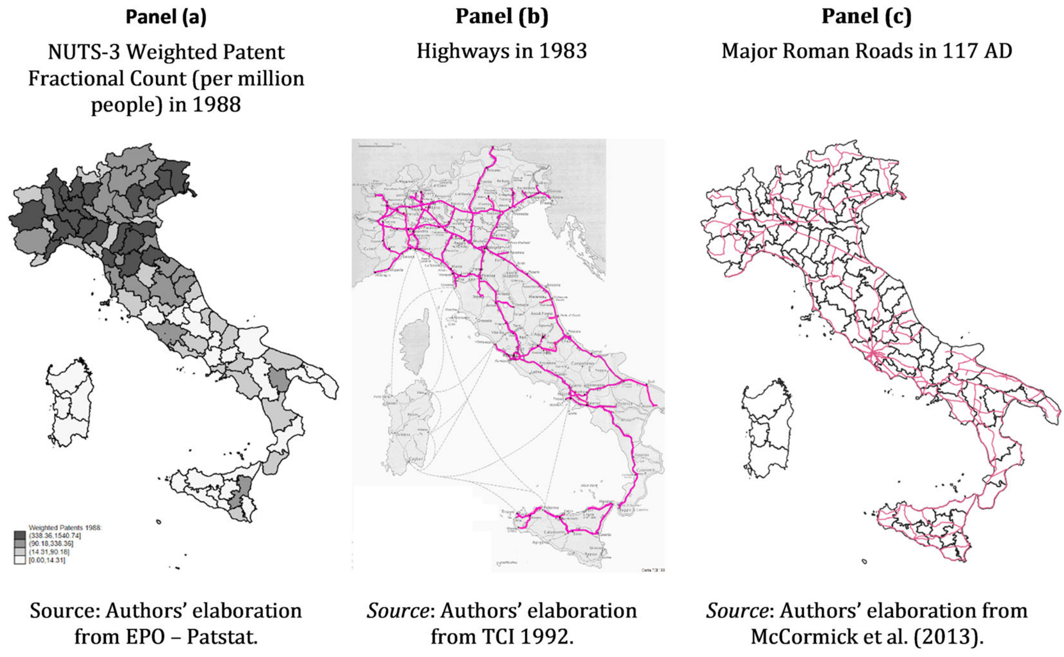

FIGURE 1 Weighted patent fractional count and road networks in Italy. EPO, European Patent Office (McCormick et al. [2013]) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Descriptive statistics

Variables	Obs.	Mean	SD
Weighted patent fractional count (per million people) 1983	89	127.39	235.50
Weighted patent fractional count (per million people) 1988	89	251.58	332.15
Number of inventors (per million people) 1988	89	21.01	24.95
Motorways length (km)	89	67.30	53.96
Major roman roads (km)	89	108.30	98.39
Surface (km^2)	89	2930.65	1594.01
Range (m)	89	758.77	510.56
Terrain ruggedness index (100 m)	89	2.30	1.61
Seat of a bishop (yes = 1)	89	0.97	0.15
Number of medium-large cities above the sample average value (yes = 1)	89	0.20	0.40

In the cross-sectional model reported in Equation (1), which is consistent with a simple model where steady-state innovation depends on motorways and innovation adjustment depends on its distance from the steady-state, $Innov_{i,88}$ refers to the natural logarithm of our innovation measure for region i in 1988, while $Motorways_{i,83}$ is the length (logarithm) of the motorways' endowment for region i in 1983. We also consider some alternative specifications of the model where we estimate the impact of the motorways network in 1983 on innovation performance in 1994, 2000, 2006, and 2012. Following a common practice in the innovation literature, we also include in the model the lagged dependent variable as an input for future knowledge, to take into account the cumulative nature of the latter, as in Agrawal et al. (2017) and Dong et al. (2020). One further advantage of controlling for the lagged dependent variable is that it should take into account most of the time-invariant (or slowly moving) unobserved heterogeneity at the regional NUTS-3 level. Indeed, as argued by Acemoglu et al. (2020) in a similar case, the lagged dependent variable may control for permanent differences in regional innovative patterns.[20] Moreover, the empirical model includes also a set of control variables, X_i. In particular, to fully account for the slowly-moving determinant of innovation, we also consider the number of inventors residing in each region in 1983, as a proxy for the regional human capital and knowledge base. In the rest of the paper, we refer to this latter variable and to the lagged dependent variable as *Innovation Controls*. In addition, we control for a set of historical and geographical characteristics.[21] *Historical Controls* include a dummy variable related to the size of the cities in each region as of 1300 CE and to the presence of a Bishop in the region at about the same period. The rationale for their inclusion is that they should capture the degree of economic development in each region, as far as back in time we have been able to go. In turn, *Geographical Controls* include measures for surface, terrain asperity, and elevation, whose inclusion should make the exclusion restriction associated to our instrument choice more likely to hold, as in the case of the historic controls (see below).[22] The β coefficient is the parameter of interest that reflects the impact of motorways endowment in 1983 on local innovative activity as of 1988, after controlling for innovative activity in 1983. Given the presence of the lagged dependent variable, Equation (1) can be interpreted in terms of the effect of motorways endowment on the growth rate of innovation between 1983 and 1988.

An important issue that needs to be investigated within the evaluation of the economic impact of transport infrastructures is related to the possibility of displacement effects. Indeed, it might be that innovation is displaced from one region to another: in other words, an increase in the highways network in one region might just be simply diverting innovative activity from nearby regions (e.g., by attracting firms or inventors in the region from nearby ones) thereby generating a zero-sum game among regions. Therefore, in the spirit of Moretti and Wilson (2014), we extend the main model of Equation (1) and we include a spatial lag to analyze whether roads infrastructure generate spillover effects in nearby regions. Specifically, we estimate the following model:

$$lnInnov_{i,88} = \alpha + \beta(lnMotorways_{i,83}) + \gamma(lnInnov_{i,83}) + \theta SpatialMotorways_{i,83} + \varphi X_i + \upsilon_i, \tag{2}$$

where:

$$SpatialMotorways_{i,83} = \sum_{i \neq j}^{I} w_{ij}\ lnMotorways_{j,83}. \tag{3}$$

The additional term, $SpatialMotorways_{i,83}$, represents, for each region i, a weighted average of the motorways stock in other regions j in 1983. Weights are built as a row normalized matrix of the inverse of the distances between any region i and j multiplied by the levels of innovative capacity, with elements $w_{ij} = (Patent_i * Patent_j)/Distance_{ij}$ such that $\sum_{i \neq j}^{I} w_{ij} = 1$.[23] Thus, the spatial term accounts for the possibility that the infrastructural endowment in a certain region might have an impact on the performance of nearby regions. The θ coefficient associated to the spatial lag allows us to detect the nature of possible spillover effects.[24] A negative and significant sign of this parameter would suggest the presence of significant spatial displacement effects on regional innovation generated by road transport infrastructure endowments in a particular region.

[20]Since the diffusion of knowledge is supported by face-to-face interactions favored by the presence of highways, one might also expect to find a measure of market potential. Indeed, we believe that the presence of the lagged dependent variable should also control for this.

[21]See Section 3 for an in-depth explanation of all the control variables.

[22]Historical controls and terrain asperity are authors' elaboration from Guiso et al. (2016) and Nunn and Puga (2012) respectively.

[23]Distant regions receive a lower weight; moreover, the presence of the number of patents gives more weight to more innovative regions, so that our weight is a proxy of economic distance, according to Corrado and Fingleton (2012). To address possible endogeneity issues associated to the presence of the patent variable, we consider the innovative capacity at the beginning of the sample period, as suggested by Corrado and Fingleton (2012) and Bottasso et al. (2014).

[24]In the terminology of LeSage and Pace (2009), we estimate a spatial X model.

Estimating the effect of road transport infrastructure investments on regional innovative capacity is a quite challenging task in terms of identification strategy since there might be simultaneity between regional technological evolution and transport infrastructure investments. In fact, such investments are typically not randomly allocated whenever policymakers tend to invest in lagging areas or in low-income and low-innovation regions, or when higher growth driven by local innovation fosters the demand for mobility and the construction of highways. Moreover, there might be omitted factors that drive both infrastructure and innovation. Possible correlation between unobservables, υ_i, and the endowment of motorways of a given region in Equations (1) and (2) would bring biased and inconsistent ordinary least Squares estimates of the causal impact of motorways on innovative performance. To address such issue, we implement one of the approaches usually adopted in the applied literature on the economic impact of infrastructure as described by Redding and Turner (2015), namely the historical route IVs one.[25] In this study, we use the ancient Roman roads network dating back to 117 AD as an instrument for the current motorway endowment of the Italian regions; moreover, for each region *i*, we build the instrument for the spatial lag presented in Equation (3) as a weighted average of Roman roads endowment in other NUTS-3 regions:[26]

$$SpatialRomanRoads_i = \sum_{i \neq j}^{I} w_{ij} \, lnRomanRoads_j. \tag{4}$$

This approach has been pioneered by Duranton and Turner (2012) that choose the routes of major expeditions of exploration between 1835 and 1850 and the major rail routes in 1898 as instruments for MSAs highways endowment. These variables have also been used in subsequent works, for example, Duranton et al. (2014) and Agrawal et al. (2017). Other ancient transport network measures have been proposed by the literature as instruments for current roads endowment. Baum-Snow et al. (2017) analyze how urban railroads and highways have influenced urban form in Chinese cities by using the 1962 Chinese transport network as instrument, while Martincus et al. (2017) consider the Inca roads built before 1530 as an instrument for the 2000s Peruvian transport infrastructure. As far as the ancient Roman road network is concerned, Garcia-López et al. (2015) first use it as an instrument for the current transport system. The authors investigate the effect of highways on the suburbanization of Spanish cities by relying on an IV approach where the instrument is represented by Spanish historical roads, namely the old Roman roads and the roads built by the Bourbons in the XVIII century. Subsequent works that have used the Roman road network within an IV approach include, among others, Percoco (2015), Holl (2016), De la Roca and Puga (2017), De Benedictis et al. (2018), and Garcia-López (2019).

The validity of the Roman roads network as an instrument for modern roads endowment has been largely discussed by the aforementioned studies, both in terms of relevance and exogeneity. Indeed, historical transport networks should be relevant because modern networks are not built in isolation from them (Garcia-López, 2019) and this hypothesis has been tested by various studies. In particular, a positive correlation between Roman roads and current Spanish highways has been shown, among others, by Garcia-López (2019) and Holl (2016). Also, Percoco (2015) and De Benedictis et al. (2018) have found a strong relationship between current and Roman roads network in Italy.[27] Another condition that our instrument has to satisfy is the exclusion restriction, whereby it should affect regional innovation only through its effect on the current highway endowment and it should be independent from contemporaneous level of innovation activity at the NUTS-3 regional level. Indeed, the validity of the instrument requires its exogeneity conditional on controls and, according to previous literature, this requirement seems to be satisfied by our chosen instrument. In particular, as argued by Dalgaard et al. (2018), Roman roads are strongly predetermined and, more in general, almost any ancient transport network may be considered as exogenous because of the time that has elapsed since it was built (Duranton & Turner, 2012). Moreover, the

[25]The other approaches are the planned route IVs and the inconsequential units approach.

[26]The weighting matrix has been constructed as the spatial matrix defined in Equation (3) using Roman roads instead of modern roads.

[27]Percoco (2015) uses Roman roads as an instrument for road accessibility, as measured by the presence of a motorway exit, while De Benedictis et al. (2018) use Roman roads as an instrument for modern roads endowment.

literature has identified military reasons as the main purposes of Roman road construction, thus excluding a direct economic reason for their location (e.g., De Benedictis et al., 2018; Garcia‐López et al., 2015). However, since geography may have influenced the construction of both Roman roads and modern motorways, in our empirical specifications we also control for a set of geographic characteristics to make our exclusion restriction more likely to hold, as in De Benedictis et al. (2018) and Garcia‐López (2019). Moreover, we argue that the inclusion of lagged innovation should take into account the impact of most slowly moving unobserved heterogeneity that might be correlated with current innovation and with any location‐specific time‐invariant growth potential that might explain the construction of Roman roads, beyond geography. Finally, we believe that possible remaining concerns for lack of exogeneity of our instrument should be substantially alleviated by the inclusion of the historical variables, that indeed should control for the degree of regional economic development in the 14th century CE.

Equations (1) and (2) are estimated by OLS and IV allowing for arbitrary correlation of the errors across nearby observations. Indeed, we account for the possibility that unobserved heterogeneity might be correlated across neighboring locations, thus leading to over‐rejections of the null hypothesis (Colella et al., 2019; Kelly, 2020). Following Colella et al. (2019), we therefore compute standard errors corrected for cluster correlation across space.[28]

5 | EMPIRICAL RESULTS

5.1 | Highways and regional innovation

We first estimate Equations (1) and (2) relying on a weighted measure of forward citation patent fractional counts aggregated at NUTS‐3 regional level. In column (1) of Table 2, we show basic OLS estimates controlling for the 5 years lagged dependent variable and the standardized number of inventors in 1983 (Innovation controls), while in columns (2) and (3), we report results obtained after including geographical and historical controls. Parameter estimates provide evidence in favor of a positive correlation between 1983 motorways stock and the weighted patent fractional count in 1988. Columns (4)–(6) report estimates of Equation (2) and suggest that the inclusion of a spatial lag does not affect the positive correlation between highways and innovation; the coefficient of $lnMotorways_{i,83}$ remains positive and significant, while the coefficient of $SpatialMotorways_{i,83}$ is not significant.[29]

To interpret the positive correlation between road infrastructure and regional innovative activity in a causal way, we address possible endogeneity issues by adopting an IVs approach. First, we estimate the reduced form of our model, that is, a specification where regional innovative activity is let to depend on instruments, as well as on innovation, geographical and historical controls. Columns (7) and (8) of Table 2 report reduced form OLS estimates and suggest that a denser Roman road network tends to significantly increase regional innovation. Again, the stock of Roman roads in nearby regions does not seem to affect levels of innovation, thus suggesting evidence in favor of the absence of spillovers effects.[30] Table 3 presents IV results and shows that the coefficient of $lnMotorways_{i,83}$ is always statistically significant, even in the presence of controls. As shown in columns (1)–(3), it has a magnitude of about 0.27–0.30, only slightly larger than OLS ones, while the inclusion of the spatial lag slightly increases its

[28]The authors propose a variance‐covariance matrix estimator that allows to obtain cluster‐robust inference in a TSLS setting with arbitrary dependence across observations. Their approach considers a circle around each observational unit that spatially bounds distance dependence, allowing for different decay processes.

[29]All estimated equations include the lagged dependent variable, whose coefficient ranges from 0.48 to 0.53 across the various specifications. Overall findings are broadly confirmed if we remove it.

[30]The estimation of the reduced form is insightful for various reasons. First, because it shows that the ancient Roman road network still has an effect on current regional innovation. Second, because the positive and significant effect of the Roman road network in the reduced form tells us that also current highways have a positive effect on regional innovation, given their positive correlation in the first stage equation (see below and Andrews et al., 2019 for an explanation). Finally, since the reduced‐form is estimated with OLS, the estimates are not affected by possible weak instrument problems (see below).

TABLE 2 The impact of motorways on innovation—OLS estimates and reduced form

Dependent variable: $lnInnov_{i,88}$	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$lnMotorways_{i,83}$	0.2539*	0.2525*	0.2233*	0.2492*	0.2494*	0.2100*		
	(0.0659)	(0.0607)	(0.0565)	(0.0645)	(0.0600)	(0.0536)		
$SpatialMotorways_{i,83}$				0.4375	0.2687	0.6885		
				(0.5789)	(0.5887)	(0.4848)		
$lnRomanRoads_i$							0.1221**	0.1268***
							(0.0621)	(0.0731)
$SpatialRomanRoads_i$								−1.0391
								(0.8018)
Innovation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography	No	Yes	Yes	No	Yes	Yes	Yes	Yes
History	No	No	Yes	No	No	Yes	Yes	Yes
Observations	89	89	89	89	89	89	89	89
R^2	0.6990	0.7038	0.7181	0.6997	0.7040	0.7196	0.7013	0.7076

Note: All specifications are estimated by ordinary least squares. $lnInnov_{i,88}$ is the weighted forward citation count of patents in region *i* in 1988. Innovation controls include the lagged dependent variable and the (ln) number of inventors (per capita) in each NUTS-3 region in 1983. Geographical controls include surface, terrain ruggedness, and elevation. Historical controls include the dummy related to the presence of a bishop and the dummy related to the presence of medium and large cities. We add one to all patents, inventors, and motorways before taking the ln in order to preserve 0 value observations. Robust standard errors corrected for cluster spatial correlation in parentheses.

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

magnitude (columns (4)–(6)). Moreover, and consistently with results in Table 2, the spatial lag is not statistically significant, thus possibly denoting the absence of spatial spillovers.

Standard errors reported in Tables 2 and 3 are estimated with the approach of Colella et al. (2019).[31] In particular, we assume spatial correlation within a threshold of 75 km, so that each region error can be correlated with other regions (errors) located within a radius of 75 km.[32] On the basis of this assumption, there are, on average, five regions in each spatial cluster.[33] It is worth noting that all results are confirmed when using heteroskedasticity robust standard errors.

It is important to discuss the exclusion restrictions underlying our interpretation of IV results. In particular, to estimate Equation (1), we consider one excluded instrument, namely the (ln) length of ancient Roman roads in each region, to account for the possible endogeneity of current highways, while the estimation of Equation (2) requires an additional excluded instrument, that is, $SpatialRomanRoads_i$ as defined in Equation (4). Therefore, in both cases, we consider just-identified models, which prevents us from undertaking Sargan-type tests for the validity of excluded instruments. Nevertheless, on the basis of the discussion reported in Section 4, we argue that, conditionally on the rich set of controls, the Roman road network is likely to be a

[31]We use the Stata command *acreg*, that computes standard errors corrected for arbitrary cluster correlation in spatial and network settings. It implements a range of error correction methods for linear regression models, OLS and two-stage least squares.

[32]Indeed, we believe that a 75 km cutoff is a reasonable value beyond which it should be safe to assume zero spatial correlation.

[33]We conduct the analysis using a uniform decay kernel. In this case, the matrix used for the computation of the variance-covariance matrix is binary. It is worth noting that results are confirmed when using Bartlett-type kernels, that is, allowing for weights in the matrix to linearly decrease as the distance increases, with values very close to one for nearby regions and almost zero for regions close to the distance cutoff.

TABLE 3 The impact of motorways on innovation—Instrumental variable estimates

Dependent variable: $lnInnov_{i,88}$	(1)	(2)	(3)	(4)	(5)	(6)
$lnMotorways_{i,83}$	0.2765**	0.2971***	0.2659**	0.3492**	0.4050***	0.4407**
	(0.1113)	(0.1078)	(0.1220)	(0.1391)	(0.1335)	(0.1771)
$SpatialMotorways_{i,83}$				−2.1884	−2.6937	−3.0157
				(1.7751)	(1.7456)	(1.9722)
Innovation	Yes	Yes	Yes	Yes	Yes	Yes
Geography	No	Yes	Yes	No	Yes	Yes
History	No	No	Yes	No	No	Yes
Observations	89	89	89	89	89	89
R^2	0.6987	0.7026	0.7172	0.6709	0.6643	0.6627
F-statistic	17.55	14.26	10.90	7.891	6.216	3.579

Note: All specifications are estimated by two-stage least squares. $lnInnov_{i,88}$ is the weighted forward citation count of patents in region i in 1988. Innovation controls include the lagged dependent variable and the (ln) number of inventors (per capita) in each NUTS-3 region in 1983. Geographical controls include surface, terrain ruggedness, and elevation. Historical controls include the dummy related to the presence of a bishop and the dummy related to the presence of medium and large cities. We add one to all patents, inventors, and motorways before taking the ln in order to preserve 0 value observations. F-statistics is the first stage Kleinbergen–Paap statistic. Robust standard errors corrected for cluster spatial correlation in parentheses.

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

valid instrument.[34] As far as the relevance of chosen instruments is concerned, we check first stage F-statistics reported at the bottom of Table 3.[35] Indeed, the robust F-statistic ("Kleibergen Paap rk Wald F-statistic") generally exceeds conventional critical values for the weak instrument test based on TSLS size.[36]

Wrapping up, overall results obtained with different estimation techniques suggest that the regional endowment of highways has a positive and significant impact on regional innovation performance. In particular, estimates imply that an increase of 10% in the length of the motorways network in 1983 leads to an increase of about 3%–4% in 1988 regional weighted patent fractional count, ceteris paribus.

To verify the validity of our results, we undertake a series of additional robustness checks. First, we replicate the analysis using two alternative measures of regional innovation performance. In one specification we rely on a measure of forward citation weighted patent fractional count which is based on the address of the applicants instead of the inventors' place of residence. Indeed, inventors and applicants (typically a firm) might not be located in the same region, so that we would end up attributing a patent to the region of residence of the inventor, although the invention was developed in a different region (where the inventor worked). It is reasonable to expect that this is more likely where the highways network is more developed. Empirical results, displayed in Appendix A (Table A1), suggest that the impact of motorways is quite similar to our baseline estimates, thus suggesting that inventors commuting is not an issue in our data. We also replicate the analysis by using an unweighted patent fractional count

[34]See also below for robustness checks that include additional controls.

[35]First stage estimates show that the coefficients of $lnRomanRoads_i$ and $SpatialRomanRoads_i$ are always positive and statistically significant at 1% level. Results are available upon request.

[36]For estimates reported in columns (4)–(6) of Table 3, where more than one endogenous regressor is included, one should refer to tables reported by Stock and Yogo (2005).

measure. As shown in Appendix A (Table A2), estimated coefficients of $lnMotorways_{i,83}$ on average remain positive and significant, even though their magnitude is somewhat lower than in Table 3.[37]

Another extension of our analysis addresses the issue of possible unobserved heterogeneity associated to different patents technology sectors. In particular, we analyze the relation between the highways stock and weighted patent fractional count at level of region *i* and technological sector *s* and we include technological sector fixed effects in the model. Following the WIPO classification, we consider five technological sectors, namely Electrical Engineering, Instruments, Chemistry, Mechanical Engineering, and other sectors. Results shown in Appendix Table A3 confirm our previous findings, even if parameter estimates are slightly smaller; moreover, the coefficients of the spatial lag variable are significantly negative, thus suggesting the presence of negative spillovers.

We further explore treatment effects heterogeneity across technological sectors by separately estimating the model for each sector. Empirical results displayed in Appendix Table A4 show that the highway network has a generally positive effect, albeit statistically significant only in the Mechanical Engineering sector and the Instruments sector, which accounts for about 50% of all patents in our sample. Indeed, the literature (see Jaffe et al., 1993; Thompson & Fox-Kean, 2005, among others) has suggested that the extent to which knowledge flows are localized (and thus possibly more or less affected by a denser highway network) might be very sensitive to the level of aggregation of patent technology classes. For this reason, we have run separate regressions at the finest level of disaggregation available in our data set, that is, for 35 technology fields. Regression results (available upon request) report interesting heterogeneous treatment effects since we find a positive and significant elasticity in 7 out of 35 technology fields, with at least one positive and significant elasticity for any of the five larger technology sectors.[38]

As part of the robustness analysis, we explore potential heterogeneous treatment effects associated to differentials in inventors density across regions. Indeed, geographic proximity favors the development of knowledge flows, learning processes and relations among inventors, which in turn might affect innovative performance. In this context, the motorways system may represent an important tool in favoring the creation of networks between scientists and organizations. Results from this analysis (Appendix Table A5) suggest that the positive effect of highways on innovation is largely driven by low innovator density regions, even if such finding should be interpreted with caution given the low *F*-statistics observed in some regressions, probably associated to the small sample sizes.[39]

Lastly, although we are aware that some regional socioeconomic characteristics might not be completely independent from regional innovative performance (because they can act as mediating factors), we replicate our main analysis after including additional socioeconomic controls that might further reinforce our exclusion restriction. In particular, we add one dummy variable for the presence of at least one airport in the region as of 1983 and one dummy for those regions with at least one university headquarters as of 1983, as further controls for regional innovation determinants.[40] Moreover, we also control for regional gross value added per employee, which is a proxy for labor productivity. Reassuringly, as shown in Appendix Table A6, all results are broadly confirmed.[41]

[37]By using these two different measures of regional innovation, we detect evidence of possible displacement effects since the coefficients of the spatial lag are in general negatively significant. However, the *F*-statistics are quite low, thus casting some doubts on estimates reliability.

[38]The seven technology fields are telecom, IT for management, measurement, microstructural and nanotechnologies, machine tools, furniture games, and Civil Engineering.

[39]See Appendix A for further details.

[40]The latter should control for the effects on innovation stemming from other transport infrastructures. Unfortunately, due to the limited availability of data at NUTS-3 level in the period considered in our analysis, we are not able to control for another important transport mode, such as the railways network.

[41]Further analysis accounts for heterogeneity associated to the north-south dimension of Italian regions. Focusing on regions located in the center-north of Italy, the IV regressions (available from the authors upon request) suggest a positive impact of the highways network on innovation however, due to the very low number of observations (about 60), these estimates are rather imprecise.

5.1.1 | Other threats to identification

In this section, we deal with some additional issues that might invalidate our identification strategy. First, it is important to recognize that most of the Italian highway network was completed by the beginning of the 1980s.[42] Although some regions experienced non-negligible extensions in their highway networks over both the 1980s and 1990s, it is important to acknowledge that, over our sample period, the highways network was, on average, quite slow-moving. This might create a bad control problem in our equation because of the presence of the lagged dependent variable if the shocks to the innovation process display serial correlation over time.[43] Since we do not know whether the innovation process displays serial correlation or not in our case, it is important to check that our main results are not affected by the presence of the lagged dependent variable.[44] Therefore, we replicate estimates of our main models reported in Tables 2 and 3 without including the lagged dependent variable. Reassuringly, all results are confirmed, both in terms of magnitude as well as statistical significance.[45]

Another concern about the validity of our identification strategy is related to the historical IV approach. Indeed, according to Flückiger et al. (2021), regions that in the past were connected by the ancient Roman road network tend to show better transport connections today and more similar production structures, associated to more homogeneity in preferences, religious beliefs and, more generally, cultural values. In turn, such similarity in cultural values tends to have important and persistent effects on cross-regional firm investments and innovative attitudes. In other words, the results in Flückiger et al. (2021) suggest that we cannot rule out the possibility that the ancient Roman roads network might affect modern regional innovative activity not only by influencing the modern highways network, but also because of its effects on cultural values, thereby violating the exclusion restriction. To address such concern, we control for a measure of regional social capital in our main regression specification, to account for the role that the Roman road network might still play on regional innovation through its effects on cultural values and social attitudes.[46] In particular, following Nannicini et al. (2013), we rely on a proxy for social capital that has often been used in the literature for the Italian case, namely the turnout in the referendum on divorce in 1974.[47] Results, shown in Appendix A, Table A8, are confirmed.[48]

5.2 | Transmission mechanisms

5.2.1 | Gravity model of innovative collaborations

As mentioned in the Introduction, within the different channels through which transport infrastructure can affect innovation, we focus on the process of knowledge creation and diffusion, both within regions and across

[42]The Italian highways network, which measured about 400 km at the end of the 1930s, began to expand rapidly after 1955 as a consequence of mass motorizations, so that, by 1970, it already measured about 4000 km. The 1970s was still a decade of significant highways building in Italy, with the network length that increased by 50%, thus reaching about 6000 km in 1980. The rate of expansion of the highways network then considerably slowed down to about 5% in each of the following decades.

[43]In this case, the coefficient of the lagged dependent variable would be biased and inconsistent, and such bias could be transmitted to the highways stock coefficient because of its sluggishness, giving raise to a possible bad control problem. This is because in Equation (1) innovation is measured as of 1988, while lagged innovation and the highways network as of 1983; with a slow-moving highways network, there can be correlation between lagged innovation and the highways network. If innovation displays serial correlation over time, the bias in the coefficient of lagged innovation could be transmitted to that of highways network.

[44]The presence of unobserved heterogeneity would lead to positive serial correlation (and to a positive bias to the highways' coefficient), while possible convergence effects in the innovation process would lead to negative serial correlation (and to a negative bias). Serial correlation would be negligible if the unobserved heterogeneity and the convergence effects cancel out (or if serial correlation is zero to start with).

[45]Results from this analysis for the IV case are presented in Appendix A, Table A7, while OLS estimates are available upon request.

[46]We are aware that social capital might fail to capture all cultural traits of a regional community; nevertheless, we think it is a very important component (Alesina & Giuliano, 2015).

[47]Data available at https://www.tommasonannicini.eu/en/works/measures-social-capital-italian-provinces-and-muni/.

[48]Interestingly, Licio (2020) finds that, for the Italian case, Roman roads are not correlated with many proxies for social capital at the NUTS-2 level. This result supports the validity of our identification strategy.

neighboring ones. By lowering the costs of knowledge flows, higher highway stock may favor face-to-face interactions among inventors and may accelerate the circulation of ideas, thus generating important knowledge spillovers that are often constrained by space.[49] In particular, we analyze whether more cross-regional travel possibilities promote interactions among inventors and better matching of ideas, thus generating an innovative process that is both qualitatively and quantitatively more significant.

Starting from our usual patent fractional count weighted for forward citations, it is useful to define the following measure:

$$\xi_{i,a,88} = PFC_{i,a,88} \times Cit_a, \tag{5}$$

where $PFC_{i,a,88}$ is the fraction of patent application a, assigned to region i in year 1988 according to the inventor place of residence, and Cit_a is the number of forward citations received by the patent.[50]

Considering Equation (5) and following the approach introduced by Picci (2010), for every patent application a and each region-pair $i - j$, the intensity of the collaboration among inventors, that is, the intensity of coauthorship, can be defined as:

$$Coauthor_{i,j,a,88} = \xi_{i,a,88} \times \xi_{j,a,88}. \tag{6}$$

This measure captures whether a patent application is within-region, that is, its inventors reside in the same region, or between-regions, that is, inventors come from different regions, and in the latter case defines the degree of collaboration. Indeed, consider the following example: application 1 has two inventors both from Region i; application 2 has two inventors located in region i and region j; application 3 has three inventors located in regions i, j, and z. For the sake of simplicity, we can consider $Cit_a = 1$ for all patent applications and omit the subscript relative to the year 1988, so that for region i, we obtain $\xi_{i,1} = 1$, $\xi_{i,2} = 1/2$, $\xi_{i,3} = 1/3$; for region $j \xi_{j,1} = 0$, $\xi_{j,2} = 1/2$, $\xi_{j,3} = 1/3$; and, finally, for region $z \xi_{z,1} = 0$, $\xi_{z,2} = 0$, $\xi_{z,3} = 1/3$. Therefore, the collaborative measures for all region pairs and for all patent applications can be calculated as follows:

$$\begin{array}{lll} Coauthor_{i,j,1} = 1 * 0 = 0, & Coauthor_{i,j,2} = 1/2 * 1/2 = 1/4, & Coauthor_{i,j,3} = 1/3 * 1/3 = 1/9, \\ Coauthor_{i,z,1} = 1 * 0 = 0, & Coauthor_{i,z,2} = 1/2 * 0 = 0, & Coauthor_{i,z,3} = 1/3 * 1/3 = 1/9, \\ Coauthor_{j,z,1} = 0 * 0 = 0, & Coauthor_{j,z,2} = 1/2 * 0 = 0, & Coauthor_{j,z,3} = 1/3 * 1/3 = 1/9. \end{array}$$

Thus, this measure takes on a zero value if the patent application has no coauthorship between inventors from different regions, while it takes on a positive value (and increasing according to the intensity of the collaboration) otherwise.[51]

Finally, the aggregate measure of collaboration among inventors of different regions is defined as the sum of Equation (6) for all patents:[52]

$$Coauthor_{i,j,88} = \sum_{a=1}^{A} Coauthor_{i,j,a,88}. \tag{7}$$

[49]Catalini et al. (2020) analyze how travel costs, and more generally geographical frictions, can influence decisions related to scientific collaborations. Based on a *DiD* design, the authors estimate the effect of a reduction in travel costs, that is, the introduction of new routes by a low-cost airline, on the rate of collaboration (and also on the types of projects pursued). Their results show that better infrastructure, and thus lower transport costs, can have a positive impact on the probability and intensity of collaboration between scientists and it is particularly beneficial for high-quality ones.

[50]It is worth noting that $\sum_{a=1}^{A} \xi_{i,a,88} = Innov_{i,88}$, the main dependent variable described in Section 4.

[51]Note that the intensity of collaboration is maximized if the total number of inventors is equally divided between two regions.

[52]See Picci (2010) for a more in-depth explanation and some numerical examples. It is worth noting that, differently from Picci (2010), we consider not only the quantitative, but also the qualitative aspect of collaborative innovation, as proxied by the number of forward citations received by the patent, namely Cit_a.

We then follow Dong et al. (2020) by relying on a cross-sectional gravity model framework (Anderson & Van Wincoop, 2003) to analyze the role of highways on the intensity of collaboration between pairs of regions:

$$\ln Coauthor_{i,j,88} = \alpha + \beta \ln Coauthor_{i,j,83} + \gamma \ln Motorways_{i,j,83} + \delta \ln Distance_{i,j} + \varphi_i + \varphi_j + \epsilon_{i,j}. \quad (8)$$

In Equation (8), $Coauthor_{i,j,88}$ is our measure of collaborative innovation among inventors located in regions i and j in 1988. $Motorways_{i,j,83}$ is the sum of the length of motorways in the two regions i and j in 1983 (see Dong et al., 2020 for a rationale of this choice) and $Distance_{i,j}$ represents the travel distance (in kilometers of highways) between each pair of regions' centroids. We also include directional (i and j) fixed effects, φ_i and φ_j, to control for any unobservable omitted regional variables.[53]

As mentioned above, there might be simultaneity between the intensity of collaboration among pairs of regions, regional technological evolution and transport infrastructure endowment. Consequently, in Equation (8), there might be correlation between unobservables, $\epsilon_{i,j}$, and the regions-pairs' endowment of highways. To address such issue, we rely on the IV estimation approach. In particular, we use the sum of the length of major Roman roads in the two regions i and j ($RomanRoads_{i,j}$) as instrument for the 1983 sum of the length of motorways in each regions-pairs. Moreover, $DistanceRR_{i,j}$ represents the travel distance (in kilometers of Roman roads) between each pair of region centroids and it is used as instrument for 1983 travel distance.

Table 4 presents results from the cross-sectional gravity model with fixed effects estimates.[54] First, we estimate the reduced form of Equation (8), that is, an empirical specification where the measure of collaboration between pairs of regions is let to depend on above-mentioned instruments, including directional (i and j) fixed effects. Column (1) of Table 4 shows reduced form OLS estimates. Results suggest that the distance between pairs of regions deters knowledge flows; however, ceteris paribus, a denser Roman roads network among them positively affects cross-regional collaborations. Finally, column (2) of Table 4 presents IV estimates and shows that the coefficient of $lnMotorways_{i,j,83}$ is positive and statistically significant, with a magnitude of about 0.190. Consistently with reduced-form estimates, this result suggests that a denser stock of motorways in each pair of regions positively affect collaborative innovation, thus favoring knowledge flows and the circulation of ideas across regions.[55]

5.2.2 | Network analysis

The estimated gravity model has shown that a denser highway network tends to favor collaborations among inventors. An interesting extension of this analysis is related to the link between regional endowment of motorways and regional embeddedness into a wider innovation network. In order explore this issue, we adopt an SNA approach, as the structure of research collaboration can be viewed as a network composed of links and nodes (Galaso & Kovářík, 2021). In particular, we investigate whether highways regional endowment favors regional embeddedness, as proxied by different measures of node centrality (Mitze & Strotebeck, 2018; Wanzenböck & Piribauer, 2018; Wanzenböck et al., 2014; Wanzenböck et al., 2015). Indeed, node centrality within a collaboration network has been found to exert a positive impact on regional

[53]It is worth noting that region (i and j) fixed effects, φ_i and φ_j, account for most of inward and outward multilateral resistances as well as regional unobservable characteristics that may influence bilateral knowledge flows (Donaubauer et al., 2018). Moreover, following Bacchetta et al. (2012), we include a full set of gravity variables (e.g., bilateral travel distances and cross-regional motorways endowment) to proxy for bilateral travel costs. We also include a 5-year lagged dependent variable, $Coauthor_{i,j,83}$, to account for most of the time-invariant unobserved heterogeneity at the $i-j$ pair level. Finally, $\epsilon_{i,j}$ is an error term.

[54]All specifications are estimated accounting for standard error clustered by region-pairs.

[55]As a further analysis, we replicate the estimates presented in Table 4 after controlling for the levels of social capital of regions i and j. Indeed, according to Flückiger et al. (2021), more connected territories in the past (through the ancient Roman road network), tend to have similar socioeconomic characteristics and to share similar cultural values, so that it can be argued that more connected territories in the past might collaborate more today, independently from the role played by modern highways networks, thus violating the exclusion restrictions. In particular, we rely on two alternative measures of social capital: $SocCapital_{ij} = SocCapital_i \times SocCapital_j$ and $SimilaritySocCapital_{ij} = 100 \times \{1 - [(|SocCapital_i - SocCapital_j|)/(SocCapital_i + SocCapital_j)]\}$. Overall results are confirmed when we add these social capital measures as control variables. Results are available from the authors upon request.

TABLE 4 Transmission mechanisms—Gravity model estimates

Dependent variable: $lnColl_{i,j,88}$	**OLS (1)**	**IV (2)**
$lnRomanRoads_{i,j}$	0.0433*	
	(0.0225)	
$lnDistanceRR_{i,j}$	−0.2875***	
	(0.0294)	
$lnColl_{i,j,83}$	0.6416***	0.6398***
	(0.0439)	(0.0436)
$lnMotorways_{i,j,83}$		0.1895*
		(0.1052)
$lnDistance_{i,j}$		−0.2966***
		(0.0301)
Region *i* FE	Yes	Yes
Region *j* FE	Yes	Yes
Observations	7921	7921
R^2	0.556	0.549
F-statistic		25.37

Note: Reduced form (OLS) and two-stage least squares estimates. $Coll_{i,j,88}$ is the aggregate weighted forward citation measure of collaboration among inventors of regions *i* and *j*. $RomanRoads_{i,j}$ is the sum of the length of major Roman roads in the two regions *i* and *j*, while $Motorways_{i,j,83}$ is the same measure calculated using motorways in 1983. $Distance_{i,j}$ and $DistanceRR_{i,j}$ are distances (in kilometers) between each pair of region centroids, calculated respectively on the basis of modern motorways and major Roman roads. We add one to the collaboration and roads measures before taking the ln to preserve 0 value observations. *F*-statistics in column (2) is the first stage Kleinbergen–Paap statistic. Standard errors clustered by NUTS-3 region-pairs in parentheses.

Abbreviation: IV, instrumental variable.

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

innovation, by increasing knowledge flows and absorptive capacity of knowledge spillovers (Owen-Smith & Powell, 2004; Whittington et al., 2009).[56]

Within this framework, it is interesting to analyze the role played by regional highway endowment in shaping node properties and network structure.[57] To explore this issue, we build a simple network of co-patenting, where nodes are represented by NUTS-3 regions, on the basis of the measure of collaboration among inventors of different regions defined in Equation (7). Following Wanzenböck et al. (2014), the weighted graph is represented by the following *n*-by-*n* collaboration/adjacency matrix:

[56]In a recent paper by Galaso and Kovářík (2021), the authors demonstrate that the national networks of collaboration play an important and positive role in patenting performance.

[57]Seminal contribution in studying how regions achieve successful placement in collaborative research networks is associated to regional characteristics is Bergman and Maier (2009).

$$\Omega_{t\,(i,j)} = \begin{pmatrix} Coauthor_{1,1} & Coauthor_{1,2} & \dots & Coauthor_{1,n} \\ Coauthor_{2,1} & Coauthor_{2,2} & \dots & Coauthor_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ Coauthor_{n,1} & Coauthor_{n,2} & \dots & Coauthor_{n,n} \end{pmatrix},$$

where $Coauthor_{i,j}$ represents the collaboration intensity between inventor located in region i and j. We also build an unweighted version of the adjacency matrix as follows:

$$\Omega_{t\,(i,j)} = \begin{cases} 0 & \text{if } Coauthor_{i,j} = 0 \\ 1 & \text{if } Coauthor_{i,j} > 0 \end{cases}.$$

Further, we compute different centrality measures to proxy network embeddedness of region i into the interregional innovation network.[58] First, we rely on the simplest way of measuring region-node centrality by calculating *Degree Centrality*, that is, the number of the adjacent edges to each region-node i. This local measure of node's embeddedness in a network can be considered as a proxy for the degree of knowledge exchange between collaborating regions. Indeed, linkages to other regions favor better access to knowledge flows so that nodes with high degree centrality can be characterized by higher local knowledge creation (Mitze & Strotebeck, 2018).

We then compute a weighted degree centrality measure, that is, *Strength*, where edges are weighted with the number of pairwise co-patenting. This measure is obtained by summing up the edge weights of the adjacent edges for each region-node. For illustrative purposes, in Figure 2, we show the graph representing the co-patenting network where the size of the nodes, representing the Italian regions, is proportional to the *Degree Centrality* and the thickness of the edges reflects the intensity of the collaboration. Third, we compute the Freeman (1978)'s *Betweenness Centrality*, an unweighted measure that reflects the power of a region to control knowledge diffusion within a network. This measure is defined as the number of shortest paths going through a region-node and measures "how often a region is situated between other, not directly interlinked, regions" (Wanzenböck et al., 2014). A higher value of *Betweenness Centrality* characterizes those regions that are more likely to influence the transfer of knowledge within the whole network and the creation of knowledge spillovers.[59] The fourth measure calculated is the *Eigenvector Centrality*. "According to eigenvector centrality, a region's centrality depends both on the number and the quality of its connections, assuming that prominent actors act as "hub" for knowledge transmission and diffusion throughout the entire network. Its calculation is based on centralities of all regions in the network in the form of assigning centrality weights that correspond to the average degree of all linked regions" (Bonacich, 1987; Wanzenböck et al., 2014).

The centrality measures discussed above represent the dependent variable of an empirical model where we analyze the role played by regional highways endowment on node properties and network structure. In particular, we estimate the following model:

$$lnC_{i,88} = \beta_0 + \beta_1(lnMotorways_{i,83}) + \beta_2(lnC_{i,83}) + \beta_3 X_i + \epsilon_i, \tag{9}$$

where $C_{i,88}$ represents the aforementioned centrality measures.[60] The empirical model includes $Motorways_{i,83}$ as defined in Section 4 and all controls X_i (innovative, geographical, historical). Finally, the inclusion of 5-year lag $C_{i,83}$ allows to control for the role of path dependencies in network formation (Mitze & Strotebeck, 2018).

[58] All centrality measures are computed using *iGraph* R Package. Note that the network also includes self-loops (i.e., a link from a node to itself) indicating those region-nodes that, despite not having co-patenting, exhibit innovative activity at time t (Abbasi et al., 2011). Therefore, we deal with a disconnected graph so that we do not consider closeness centrality, not well-defined for disconnected graphs.

[59] Mitze and Strotebeck (2018), in their Supplementary data online, provide a useful interpretation of various centrality measures in the case where regional nodes are used as the unit of analysis and highlight main examples of applications in the literature.

[60] See Bergman and Maier (2009), Wanzenböck et al. (2014), Wanzenböck et al. (2015), Mitze and Strotebeck (2018), Huggins et al. (2020) as examples of other works where measures of network centrality are used as the dependent variable, albeit differing in their estimation methods.

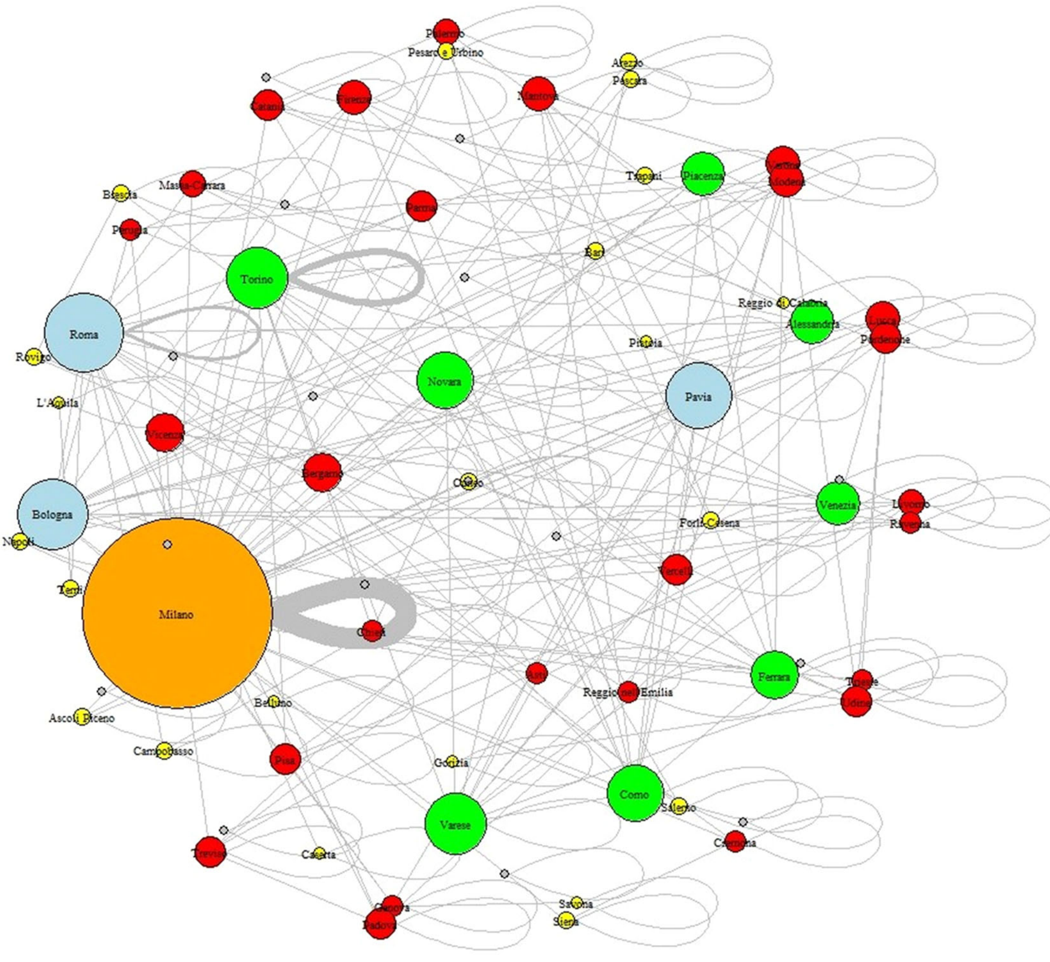

FIGURE 2 Co-patenting network in 1988—Italian NUTS-3 regions by degree centrality [Color figure can be viewed at wileyonlinelibrary.com]

Since there might be simultaneity between the regional embeddedness and transport infrastructure endowment, and there might be omitted factors that drive both infrastructures and nodes centrality in the network, to tackle this issue we rely on an IV approach and we choose to consider the instrument introduced in Section 4, namely $lnRomanRoads_i$. In columns (1)–(4) of Table 5, we report reduced form OLS estimates of Equation (9), while IV results are shown in columns (5)–(8). It is worth noting that we compute standard errors corrected for arbitrary cluster correlation in a network setting.[61] Estimates results confirm the importance of roads infrastructure in fostering regional embeddedness (as proxied by centrality measures) into an interregional collaboration network. This result holds across different specifications that use alternative centrality measures.[62] In particular, reduced form OLS estimates suggest that a denser Roman road network tends to significantly increase regional centrality, with coefficients of $RomanRoads_i$ ranging from 0.0084 to 0.2836. As far as IV estimates are concerned, results suggest that a 10% increase in the length of motorways leads to a 1.5% and 6.5% increase in *Degree* and *Strength*

[61]In particular, we specify a distance cutoff equal to five geodesic paths, beyond which the correlation between error term of two observations is assumed to be zero. Overall results are confirmed when using different distance cutoffs and when using the usual spatial setting.

[62]Results hold even when introducing the spatial lag, both in the reduced form and using the IV approach.

TABLE 5 The impact of motorways on regional embeddedness—Reduced form and IV estimates

Dep. var. *ln*:	*Degree* OLS (1)	*Strength* OLS (2)	*Betw.* OLS (3)	*Eigenv.* OLS (4)	*Degree* IV (5)	*Strength* IV (6)	*Betw.* IV (7)	*Eigenv.* IV (8)
$lnRomanRoads_i$	0.0635* (0.0254)	0.2836** (0.0730)	0.1530** (0.0434)	0.0084** (0.0031)				
$lnMotorways_{i,83}$					0.1579*** (0.0818)	0.6507** (0.1546)	0.3307** (0.0705)	0.0189** (0.0073)
Innovation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geography	Yes	Yes	YesS	Yes	Yes	Yes	Yes	Yes
History	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	89	89	89	89	89	89	89	89
R^2	0.563	0.672	0.381	0.637	0.612	0.693	0.427	0.657
F-statistic					12.28	17.97	24.45	21.96

Note: Specifications are estimated by OLS in columns (1)–(4) and by two-stage least squares in columns (5)–(8). The dependent variable is $lnC_{i,88}$ and refers to the alternative metrics used to compute the centrality of each region *i* in 1988. Innovation controls include the lagged dependent variable and the (ln) number of inventors (per capita) in each NUTS-3 region in 1983. Geographical controls include surface, terrain ruggedness, and elevation. Historical controls include the dummy related to the presence of a bishop and the dummy related to the presence of medium and large cities. We add one to all centrality measures, inventors, and motorways before taking the ln in order to preserve 0 value observations. *F* is the first stage Kleinbergen–Paap statistic. Standard errors corrected for network clusters in parentheses.

Abbreviation: IV, instrumental variable.

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

Centrality, respectively. Moreover, a statistically significant increase of regional centrality is also detected when *Betweenness* and *Eigenvector Centrality* are considered (3.3% and 0.2%, respectively).[63]

These findings confirm that highways regional endowment favors regional embeddedness into a wider inter-regional innovation network, thus helping to explain the link between motorways and innovation. In fact, as suggested by the literature (e.g., Owen-Smith & Powell, 2004; Whittington et al., 2009), regional-node centrality has been found to positively affect regional innovative performance, by increasing knowledge flows and absorptive capacity of knowledge spillovers.

5.3 | ICT and roads

As we explained in the introduction, in this study, we focus on the relationship between regional innovative capacity observed in 1988 and the 1983 regional motorways stock, since we believe that these years of observations are not affected by the 1990s Internet revolution. Since the ICT has brought about revolutionary changes in the way people work, communicate, learn, spend time, and interact (Jorgenson & Vu, 2016), it is

[63]According to the above-mentioned findings in Flückiger et al. (2021), one may argue that areas with significant Roman roads endowment might have more cultural relations with other areas and thus also have more central positions in the co-patenting network. To deal with this concern, we replicate the analysis after including, in the set of controls, the turnout in the referendum on divorce (1974) as a measure of social capital (Nannicini et al., 2013). All results in Table 5 are confirmed. Results available upon request.

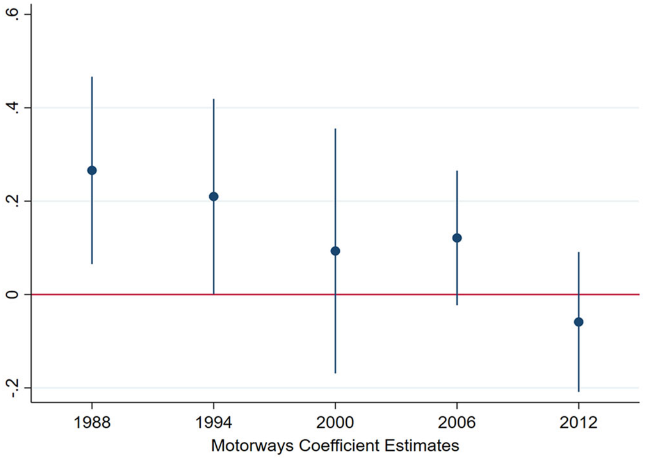

FIGURE 3 The impact of 1983 motorways endowment on innovation over time [Color figure can be viewed at wileyonlinelibrary.com]

interesting to investigate whether highways infrastructures that had been built in 1983 still have an important role in shaping knowledge flows when new communication technologies have been made available.

To analyze the long-term effect of highways, we explore the impact of the 1983 regional highways endowment on regional innovation performance observed some years later. In particular, we estimate the baseline model for 5 different years, namely 1988 (as in Table 3), 1994, 2000, 2006, and 2012.

Figure 3 shows the time path of our coefficient of interest ($Motorways_{i,83}$) estimated with the IV method. In 1994 the coefficient slightly decreases in magnitude with respect to its 1988 value, but remains positive and significant. This may reflect the fact that the Internet revolution is still in its early phases, especially in Italy. The transition to digital media appears not yet complete and the role of road infrastructure remains persistent. On the other hand, 10 years after the ICT revolution the impact of 1983 motorways endowment on regional innovation is no longer statistically significant, although only marginally so in 2006. The same result is clearly more evident as of 2012.

Although it seems natural to attribute the declining importance of the 1983 motorways network for regional innovation to the ICT revolution, it is important to discuss a possible complementary explanation. Indeed, over the same period congestion in the Italian motorways network increased substantially. By way of example, the number of vehicles (kilometers) traveling over Italian motorways over the period 1990–2007 raised by more than 60%, while the motorways network increased by just 11% over the whole period 1983–2007. Such an important increase in traffic levels over the motorways network might have significantly attenuated its role as a driving force for regional innovation. Unfortunately, the data on vehicle (kilometers) at regional level are not available, so that we cannot control for the different degrees of congestion over time.[64]

6 | CONCLUSIONS

In this study, we assess the impact of motorways endowment on regional innovative performance. We estimate an empirical model that links the Italian NUTS-3 regional innovative performance in 1988 to the stock of regional motorways infrastructure 5 years earlier. We address the endogeneity of the stock of highways with an IV approach, using the ancient Roman roads system dating back to 117 as the excluded instrument.

[64]It is worth noting that we replicate this analysis also excluding the lagged dependent variable from the set of controls. Comfortingly all results are confirmed.

Main results suggest that the 1983 highways network had a positive and significant impact on 1988 regional innovative performance; in particular, an increase of 10% in the length of motorways is associated to a 3%–4% increase in the number of patents, a magnitude that is very similar to that reported by Agrawal et al. (2017) for the US MSAs and somewhat larger to that in Dong et al. (2020) for Chinese cities.

Interestingly, we find that this sizeable economic effect tends to decline over time and persists only until the first half of the 1990s, probably because the onset of the Internet revolution has made highways less crucial for knowledge diffusion, or because of the increasing congestion which took place on Italian motorways in the most recent period.

We also find significant heterogeneous treatment effects according to the technology class, suggesting that avenue for further research might be to understand why a more developed highways network tends to stimulate innovation only in certain technology classes.

Our results are robust to a series of sensitivity checks, such as the consideration of different patent metrics (weighted and unweighted for future citations), of different criteria to attribute the patent to a specific region (e.g., depending on the applicant or the inventor region), the use of standard errors robust to spatial correlation and the consideration of the region or the region-by-technological patent class as unit of analysis. We also show the existence of significant heterogeneous effects, as motorways display a much stronger effect in low density regions, where local interaction requires longer distances to be traveled.

Moreover, according to our estimates of a gravity model, it seems that one possible economic mechanism driving our findings is related to the improved knowledge diffusion process associated to denser motorways networks, that favor collaborations among inventors living in different regions, as shown by Dong et al. (2020) for the case of high-speed trains in China. Moreover, by relying on an SNA approach, we also provide evidence that highways can play an important role in determining regional embeddedness into a wider collaboration network, that in turn may favor innovation.

Finally, we find weak evidence in favor of negative spillovers across regions, suggesting that some spatial reorganization of the innovative activity might be at work. However, since this result is not robust across all estimated models, we believe it deserves closer scrutiny in further research, possibly with more spatially disaggregated data, as suggested by Redding and Turner (2015).

ACKNOWLEDGMENTS

The authors thank seminar participants at the 61st Conference of the Italian Economic Association and the 15th North American Meeting of the Urban Economics Association (UEA) 2021. A previous version of this paper was included in the PhD dissertation of Marta Santagata and Simone Robbiano.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the European Patent Office. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from https://www.epo.org/ with the permission of the European Patent Office.

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How to cite this article: Bottasso, A., Conti, M., Robbiano, S., & Santagata, M. (2022). Roads to innovation: Evidence from Italy. *Journal of Regional Science*, 1–25. https://doi.org/10.1111/jors.12583