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From the historical Roman road network to modern infrastructure in Italy

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Abstract

The road system built during the Roman Empire continues to have a significant impact on modern infrastructure in Italy. This paper examines the historical influence of Roman roads on the development of Italy's motorways and railways. The empirical analysis demonstrates how modern Italian transport infrastructure largely follows the path of the consular trajectories established by the network of Roman roads. These ancient roads, being paved and connecting the extremes of the Italian peninsula, have endured over time, serving as the foundational physical capital for the development of the current transport network. Overall, this research highlights the enduring legacy of the Roman road system and the robustness of Roman roads as an instrument in determining the causal effect of modern infrastructure.

KEYWORDS

first stage, infrastructure, Italy, long-term effects of history, motorways, railways, Roman roads

> And what was said by Homer, 'The Earth was common to all', you (Rome) have made a reality, by surveying the whole inhabited world, by bridging rivers, by cutting carriage roads through the mountains, by filling deserts with stationes, and by civilising everything with your way of life and good order. (Aelius Aristides Orat.26.101).

1 | INTRODUCTION

The role of infrastructure in promoting economic development has long been recognized in the literature (Banerjee et al., 2020; Donaldson & Hornbeck, 2016; Flueckiger et al., 2023; Ramcharan, 2009). The development of transport infrastructure, in particular, has been shown to have had a positive, direct, or indirect impact on economic growth by improving access to domestic and international markets, reducing transaction costs, and fostering urban development (Atack et al., 2010, 2022; Fishlow, 1965; Fogel, 1964; Hornung, 2015).

In recent years, researchers have increasingly turned to historical transportation infrastructure projects as an instrument of identification of the causal impact of infrastructure investments on economic outcomes. For instance, Donaldson and Hornbeck (2016) and Donaldson (2018) examine the railway expansion in the United States and in colonial India and their effects on trade costs and land values, respectively, while Jedwab et al. (2017) and Berger and Enflo (2017) provide similar evidence for urban growth in Kenya and Sweden. Volpe Martincus et al. (2017) analyze the case of Peru and use the Inca road network (built by the Inca Empire before 1530) as an instrument for the current road infrastructure.[1]

This paper contributes to this growing literature by providing a methodological framework for examining the exogeneity and relevance of ancient transport infrastructure. Specifically, we focus on the Roman road network, constructed by Romans more than 2000 years ago, and analyze its validity as a historical instrument in the context of modern-day applied economics, focusing on Italy.

The contributions of this paper are, therefore, twofold. On the one hand, the paper provides the first stage of an instrumental variable empirical strategy, establishing the exogeneity and relevance of the instrument. On the other hand, it discusses the specific case of Italian transport network, its role in connecting Italian regions,[2] and its association with growth and welfare.[3] We demonstrate that the Roman road system meets the key criteria for a valid instrument and is positively connected with the construction of the existing Italian infrastructure.

Italy is a unique case study to examine the relationship between historical infrastructure investment and current economic development. The Roman road network, one of the largest and most extensive investments in infrastructure in history, was denser in Italy, where its expansion began, and Rome can be viewed as the "point source outbreak" of the Roman conquest pattern, which took several centuries to unfold. The Roman Empire had its core in Italy, and as a result, roads were built throughout the entire peninsula. This aspect introduces an important element that has a bearing on the economic fortunes of Italy today. Since the Middle Ages, Italy has been ruled by various foreign powers, and the current unified territory is culturally and administratively diverse. Although the central government exerts the primary influence in determining institutions, national regulations operate differently within the country, implying that local factors impact the functioning of institutions.[4] This work shows that Roman roads have had a positive impact on current transport systems, irrespective of the varied historical paths within the Italian territory.

Building on the literature examining the long-term effects of historical events on current economic development (Nunn, 2009), this paper explores two different dimensions of Roman roads: the persistent effect of history and the mechanism linking past with present. On top of that, the paper also contributes to the literature on the rise, development, and growth of Italian cities (Accetturo & Mocetti, 2019). Along this line of research, Malanima (2005) describes the long-term urbanization process in Italy, highlighting the forces and balances between rural and urban areas that drive labor productivity. Bosker et al. (2013) show how the geographical location of a city, such as being connected to a major Roman road or a Roman hub, can impact its population growth. Percoco (2013) uses historical city characteristics to instrument

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[1] Other works address other means of transport. Fajgelbaum and Redding (2014), for instance, look at Argentina and the reduction of international transport costs generated in the late nineteenth century by the introduction of large steamships.

[2] In 2016, 18% of the value of extra-EU28 exports in goods was by road. In Italy, it was 21% (http://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_goods_by_mode_of_transport). Within Europe, road freight transport is predominant and represents approximately three-quarters of the total. In Italy, this share is even greater.

[3] See Roberts et al. (2020) for a quantitative review of the literature aimed at estimating the impacts of large transport infrastructure projects: transport investments may be beneficial for welfare, equity and inclusion, but some heterogeneity can exists at the subnational level.

[4] Crescenzi et al. (2016) stress the importance of the quality of regional government for the positive economic returns of transport investments at the local level.

firm and employment density and estimates their role in income growth. In line with these studies, this paper emphasizes the role of Roman roads.

The unit of analysis is the 10 × 10 km grid cell level,[5] and the study employs a comprehensive list of controls to capture geographic, urban, and historical factors that are crucial to determine both old and modern transport networks.

As far as the exogeneity of Roman roads, historians have well reported that Romans built their roads, especially the major (consular) ones, to support their military campaigns (Finley, 1973; Laurence, 1999; Temin, 2013). While goods were transported mainly by sea before and during the Roman Empire (Flueckiger et al., 2023), the mobility of people, for purposes other than military, was limited. The ability to move troops across the Italian peninsula required roads that could quickly and easily reach military outposts. Roman roads were constructed as straight lines between strategic military points (Bishop, 2014; Hindle, 1998; Welfare & Swan, 1995) and used engineering techniques to overcome natural barriers (Bishop, 2014; Poulter, 2010; Von Hagen, 1967). The topography of the territory was the primary factor in determining the road network's construction, as high elevation, steep slopes, and terrain coverage forced the trajectory of road segments. In addition to geography, the proximity of roads to pre-existing human settlements and other civil infrastructure may have also contributed to determining the direction, leading to the subsequent development. This paper provides new empirical evidence that relates the presence of pre-Roman cities and amenities, along with geography, to the length of Roman roads. The analysis shows how Romans were motivated to build roads to overcome geographical barriers, first point of this paper. Once a grid cell was selected to host a road, the role of geography vanished, and more urban and economic factors became crucial in determining the length of the road.

Nowadays, the construction of the transport infrastructure does not conform to the rules followed by ancient constructors. On the one hand, the presence of motorways and railways is not a random-process, driven essentially by economic and urban centers. On the other hand, modern transportation systems take advantage of old infrastructure, especially when the landform creates construction difficulties. This paper explores the relationship between Roman roads, motorways, and railways, controlling for a set of geographical and market access variables. It demonstrates the benefits of the existence of ancient roads for modern infrastructure: areas where the Roman road network was denser have more railways and motorways today. This is the main finding of the paper. Major Roman roads are the main predictor of the modern transportation infrastructure in Italy. The results are robust to different controls and hold when minor (secondary) roads are also included in the analysis.

The paper is structured as follows. Section 2 provides an overview of the literature. In Section 3, the available data on Roman roads are presented, and the exogeneity of their path is discussed. Section 4 presents the empirical validation of historians' argument that Romans did not build their roads with the intention of connecting economic centers. Section 5 examines the relationship between ancient and modern infrastructure. Finally, Section 6 concludes.

2 | THE PERSISTENT EFFECT OF HISTORICAL ROMAN ROADS

In more than two decades, historical economics has evolved in several directions, examining different historical epochs and geographical settings.[6] The focus on historical infrastructures has accounted for a large share of this literature, and the Roman Empire and its network of roads have attracted significant attention in the last years. Roman roads were part of an integrated Roman economy (Temin, 2013), and beyond their strategic role in facilitating the movement of military troops during the enlargement of the Empire, the Roman road infrastructure has been found of having an enduring impact on different aspects of modern economy.

The growth of cities that followed the construction of Roman roads is one of these aspects. Larger cities were more likely to be located on a major Roman road, which determined the possibility of a minor urban center becoming a hub city (Bosker et al., 2008). According to Buringh et al. (2012), the influence of Roman domination on

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[5] On the equator this is roughly equivalent to a grid resolution of 300 arc seconds (0.0833°).

[6] For a critical review of the persistence literature see Abad and Maurer (2021).

subsequent urbanization and development can be traced back to military settlements that evolved into mixed civil–military locations upon the arrival of civilians. Both major and minor Roman roads identified those Roman settlements that led to a market economy in north-western Europe. In a similar vein, Bosker et al. (2013) suggest that Roman roads played a crucial role in facilitating trade between cities. The Roman road position is used to identify those settlements that could benefit from a close land-based transportation. Since similar standards and techniques were adopted for its construction, the road network was homogeneous throughout the entire Roman Empire. This feature is used to explore the reasons behind the growth of Europe and the Islamic world.[7] Bosker and Buringh (2017), instead, identify the effect of both first- and second-nature geographical features, such as proximity to water- or land-based transportation, the existence of agricultural possibilities, and accessibility, in determining the location of cities during the early phases of the formation of European urban centers. Locations on a river, by the sea, close to a road or, even, where two or more Roman roads crossed, affected the possibility of a settlement developing into a city.[8] The different role of land-based transportation compared to navigable waterways is also explored by Michaels and Rauch (2018). From the Early Middle Ages until the beginning of the Industrial Revolution, French settlements, compared to the British ones, were located three times closer to old sites of Roman towns, and nowadays towns in Britain resettled more than in France. During the Middle Ages, the deterioration of road quality and the increasing improvement of water transportation reshaped Britain's urban network.

The Roman road network has also been shown to facilitate the provision of public goods, fostering city growth and denser infrastructure in the Roman part of modern Germany (Wahl, 2017) and promoting economic development (Dalgaard et al., 2022) and interregional trade in Western Europe (Flueckiger et al., 2022). In the paper by Wahl (2017), the presence of ancient Roman roads is instrumental in dividing the area that corresponds to contemporary Germany into a Roman and a non-Roman part. The *Limes Germanicus* wall is used as a geographical discontinuity to test whether the formerly Roman part of Germany shows greater night-time luminosity than the non-Roman one.[9] Dalgaard et al. (2022) use the network of roads constructed during the Roman Empire to demonstrate the provision of public goods as a channel of persistence of economic development. The Roman infrastructure density predicts contemporary road density and economic activity. The result is corroborated by comparing the European region with the Middle-East and North Africa territories.[10] Similarly, Flueckiger et al. (2022) find that the Roman road network, by shaping the economic geography of the Empire, positively affected the development of regional economic hubs, which continued to thrive even after the collapse of the Roman Empire. Current connectivity and trade patterns reflect those traced in ancient times by the Roman roads.

3 | THE ROMAN ROAD NETWORK

The Roman road network began to expand simultaneously with the expansion of Rome in the fourth century BC. While the Romans built roads to connect settlements and cities, the main reason for constructing paved extra-urban consular roads was purely military, to quickly deploy troops to the insecure borders of the Empire.[11]

The earliest strategic consular Roman road was the Via Appia, named after the Roman censor Appius Claudius Caecus and constructed in 312 BC. The road, constructed in straight segments, was built in a south-easterly direction from Rome to Capua, close to Naples, to ensure a steady supply of fresh troops for the war against the

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[7] However, Bosker et al. (2013) remark the limited and weak role of Roman roads in determining the urbanization of the Islamic world.

[8] In the pre-1600 period, being located at a hub of Roman roads was beneficial for a settlement; in the post-1600, this advantage becomes insignificant or even negative (Bosker & Buringh, 2017).

[9] The transmission mechanism is attributed to the enduring effect of the Roman road network, positively affecting cities' agglomeration and the development of transportation infrastructure (Wahl, 2017).

[10] Since in Africa the wheel was substituted by camels, Roman roads were not maintained and cannot explain current economic performance. In Europe, instead, Roman road maintenance offers a valid proof of the persistence of infrastructure over time (Dalgaard et al., 2022).

[11] Consular roads were not built either for trade purposes, largely managed by navigation across the Mediterranean Sea, or for civilian transportation (Chevallier, 1976).

Samnites. The Appian Way, known as the *regina viarum*, was subsequently extended to reach Beneventum (modern Benevento), Tarentum (modern Taranto), and finally Brundisium (modern Brindisi) on the Adriatic coast. After the construction of the Via Appia, miles and miles of roads were built, covering the entire Italian peninsula, including the two main islands, Sicily and Sardinia.[12] In Italy, the network of Roman roads was dense and widespread, and the Romans classified their roads into primary (major/consular) and secondary (minor) (Supporting Information: Figure A1—included in Appendix A—provides a representation of the main consular Roman roads that crossed the Italian territory). Major Roman roads led directly to Rome if placed in Italy or to Italy if running outside current Italian borders. They were linked to each other, forming a network of military communications, while secondary roads linked military roads to cities and settlements (Bosker et al., 2013).

The raw data on the Roman road network have been digitized by McCormick et al. (2013) from the Barrington Atlas of the Greek and Roman World (Talbert, 2000).[13] The resulting Digital Atlas of Roman and Medieval Civilizations (DARMC) comprises 7154 segments of ancient Roman roads that existed at the peak of the Empire, corresponding to the death of Trajan in 117 AD. Each segment is assigned with a unique identifier, and the roads are composed of multiple segments.[14] The network spans 36 countries across Europe, Africa, and Asia, and the road segments are classified according to their level of importance (e.g., major and minor) and certainty (e.g., certain and uncertain). Supporting Information: Figures A2 and A3 in Appendix A depict Roman roads by importance and certainty.[15]

The total length of the Roman road network is 192,861 km. For the purposes of this paper, we focus on the Italian road infrastructure at the 10 × 10 km grid cell level, as computed by Licio (2021). Figure 1 displays the old road system for Italy, which constitutes 10% of the entire network, with 1817 segments spanning a total of 19,593 km in 2076 out of 5111 10 × 10 km grid cells. Of these grid cells, 1359 contain major roads and 1032 contain minor roads: 315 contain both minor and major roads, 717 contain only minor roads, and 1044 contain only major (consular) Roman roads.

3.1 | Exogeneity

The exogeneity of the Roman road infrastructure requires careful consideration.[16] Although Roman roads were constructed for military purposes (major roads in particular), it cannot be excluded that some minor roads were built to reach economically prosperous and flourishing territories and that these conditions could have lasted until the present day.[17] The analysis of the path followed by Roman roads is presented in Supporting Information: Appendix C. This section compares the ancient roads with two distinct exogenous paths: a linear path, which connects origins and destinations with a straight line, and a least-cost path, which is based on the topography of the terrain.[18]

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[12] Starting from the city of Rome, the expansion of the road network covered six centuries.

[13] The data, in shape file format, allow spatial analysis for the Roman and medieval worlds using a Geographic Information System (GIS) coding.

[14] As an example, the Via Appia is composed of 67 different segments. Roads are not classified as such and have to be reconstructed assembling the different segments. For brevity, from now on, the terms “road” and “road segment” will be used interchangeably.

[15] Certainty refers to the path followed by the road segment. All segments are always certain in their existence and in their Roman origin; what makes a road “uncertain” is the imprecision in the georeferentiation of the path followed by the road: some stretches of roads got destroyed or abandoned through the ages and for some of them there is neither archeological nor historical evidence.

[16] A considerable amount of time elapses between planning a road and its actual completion (Brooks & Hummels, 2009). From this perspective, road infrastructure can be considered as an exogenous variable. The case of old infrastructure would appear to be different. Donaldson (2018) argues that the effect of historical transportation infrastructure is characterized by a potential simultaneity problem: roads and railways are often constructed to connect regions already active in trade, while interregional trade relations are often forged after the construction of infrastructure or road improvements.

[17] Chevallier (1976, p. 116) points out that “As a rule, earlier sites were avoided by Roman roads, especially the great Imperial highways, which were unconcerned with local interests and small settlements. […] The road often attracted the village, but when the ancient road itineraries name a civitas, it does not mean that the route went through the town itself: occasionally it simply skirts its territory”. Bosker et al. (2013) support the view that the reverse causality is not an issue in the case of Roman roads, since they favored the subsequent expansion of urban centers in those territories where roads passed through, rather than being constructed for already existing settlements.

[18] The Roman road system appears conforming more to a geometrical network of straight roads than to a most geographical advantageous one. See Supporting Information: Appendix C for details.

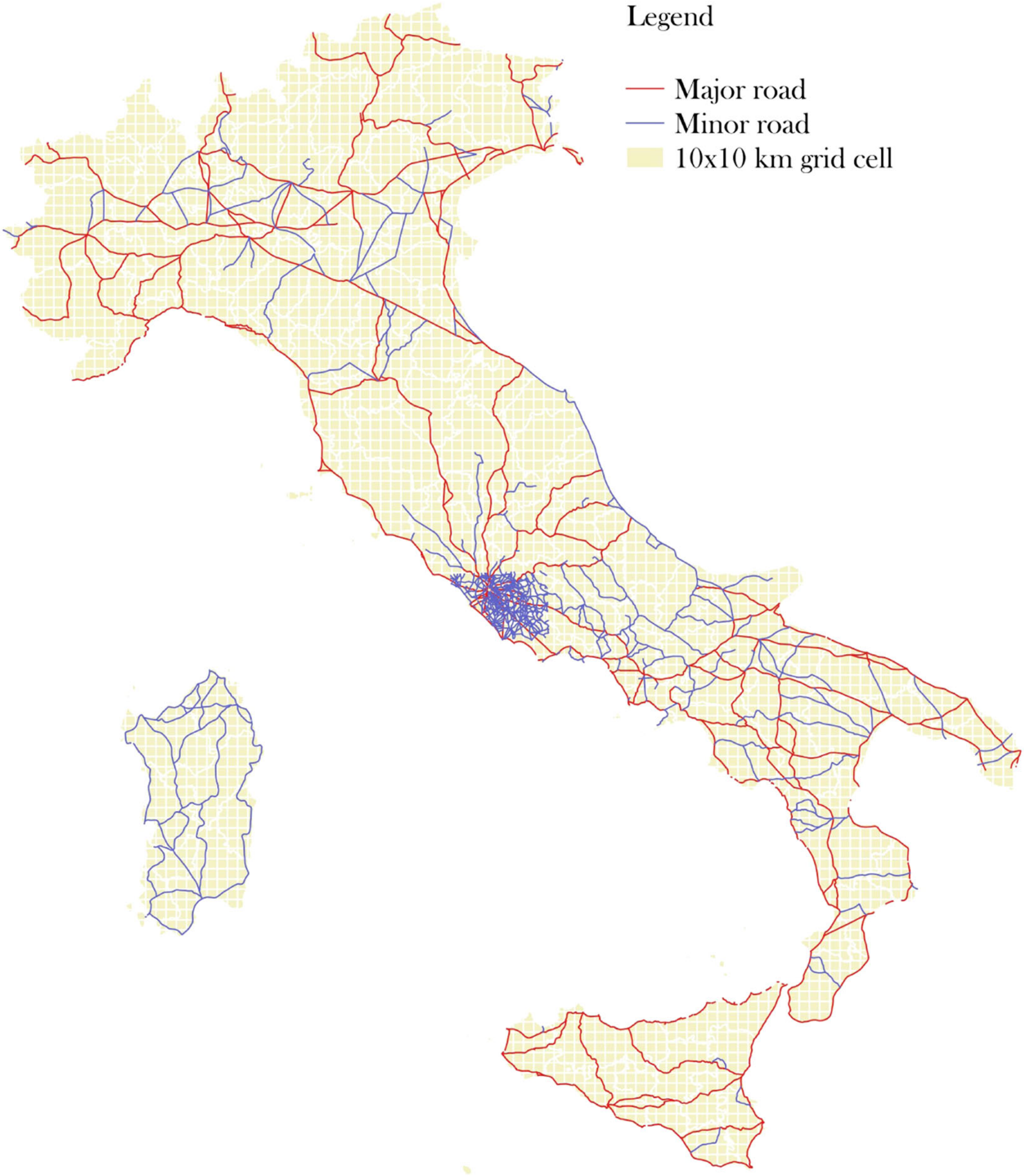

FIGURE 1 Roman road layer and Italian 10 × 10 km grid cells. *Source*: Authors' elaboration from McCormick et al. (2013), "Roman Road Network (version 2008)," DARMC Scholarly Data Series 2013-5, and from Istat data (2011).

3.1.1 | Why and how did Romans build roads? The "military and engineering reasons"

As reported in the Dictionary of Greek and Roman Antiquities, "The public road-system of the Romans was thoroughly military in its aims and spirit: it was designed to unite and consolidate the conquests of the Roman people, whether within or without the limits of Italy proper" (Smith, 1890). Even after construction, it had no significant immediate economic impact, since the cheaper modes of goods' transport in that historical epoch were by river or sea (Finley, 1973). More specifically, as Laurence (1999) clearly explains, roads were planned and designed to provide troops with the essential means in terms of subsistence and support, to guarantee efficient repositioning, and to facilitate army movements. Because of this original purpose, roads were straight, as level as possible, often stone-paved, cambered for drainage, and equipped with safe stops along the way.[19]

The direction of the Via Appia,[20] the first large strategic consular road, exemplifies its military purpose and how the ultimate aim to reach some strategic territories resulted in a long road that passed through areas of no interest to Romans but that benefited from the presence of the road.[21] From 312 BC on, it was constructed in segments, following the progress of military campaigns during the Samnite Wars, and was completed in 191 BC when it reached Brindisi.

At the end of the fifth century BC, the Italian peninsula was under the control of the Celts and the Gauls in the North, the Romans in the central-western part (upper part of Figure 2), and the Samnites and the Greek colonies (Magna Graecia) in the South. It was precisely at that time that the Romans decided to build the first section of the Via Appia (lower part of Figure 2) and started to show interest in the southern part of Italy. Also, the Samnites, an Italic population living in southern-central Italy, were interested in those territories. At first, the Romans and the Samnites concluded a nonaggression pact, agreeing to expand their possessions in different directions, but this treaty was irremediably broken when these directions clashed. From obtaining new lands for the growing Roman population, the ultimate challenge for the Romans was the conquest of Magna Graecia and extending their control over the Mediterranean Sea, where most of the trade occurred (Figure 3).

In 238 BC, the Romans controlled the entire central and southern parts of the Italian peninsula (upper part of Figure 3); the Via Appia was extended south-eastwards (lower part of Figure 3), reaching Brindisi. The stepwise extension to Brindisi meant that the troops could sail from this port, landing on the Macedonian coast thanks to ally ports along the opposite coastline, like Durres (upper part of Figure 4). The Via Appia facilitated the conquest of Greece, as shown in the lower part of Figure 4.

Three facts emerge from the above description: (1) the instrumental role of roads in the military conquest of new territories; (2) the development and expansion of roads by strategic points: the Romans built new road segments starting from tactical cities or outposts (*Stationes*); (3) the stepwise construction of roads, with a view to future expansion. This suggests that some territories were crossed by Roman roads although the Romans themselves had no economic, military, or tactical interest in those areas. In other words, those territories benefited from the presence of Roman roads merely by chance because they were situated midway between the origin of a road's segment and its strategic destination.

Additional and definitive proof of the military function of roads and their segmented design can be found in the Via Annia, the most significant road in southern Italy. Constructed in 132 BC, it stretched 475 km and was commissioned by the Roman judiciary to connect Capua to Regium (modern Reggio Calabria) and ensure military power over the *Civitas foederata Regium*.[22]

The road's path was arduous, as depicted in Figure 5, following the western coastline of Campania and Calabria. From Capua, it led to Salernum (modern Salerno), then to Regium, passing by various Roman Stationes, including

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[19] The “military reason” is also strongly supported by the Latin literature. “After having pacified Liguria, Aemelius had his army build a road from Piacenza to Rimini to join the via Flaminia” (Livy, 59 BC–17 AD). In his “Encyclopedia of antiquities, and elements of archaeology, classical and medieval,” Fosbroke (1843) reports that the Anglo-Saxon ancestors named the Roman roads “military ways” and that they thought the construction of small roads had more military utility than large ones. Chevallier emphasizes the importance of the army's role in the case of main roads. He remarks that “[…] the majority of main roads were pioneered by military operations. For example, on its return from the first Samnite war (343-40), the Roman army did not come back along the via Latina, but followed the coast through the territory of Aurunci, thus blazing the trail of the Appia on a line that had already been known to traders, at least since the hegemony of Etruria. In the early third century, operations against the Umbrians of Mevania and Narnia and against the Senones took into account the route that became the Flaminia. Great strategic roads were built by the military in Gaul under Agrippa from BC 16-13 in Dalmatia and Pannonia under Tiberius from AD 6-9, in the Rhineland and the Danube valley under Claudius, and in Asia Minor under Flavians” (Chevallier, 1976, p. 85).

[20] See Berechman (2003) for a recent and in-depth description of the economics of the Via Appia.

[21] The Romans decided to build their first road south-easterly, although the economic development of the time was concentrated in the southwestern part of Italy in those territories corresponding today to the NUTS2 regions of Campania, Calabria, and Sicily.

[22] In the second century BC, Romans had already secured the entire South of Italy and they needed a road that easily connected Rome with the foot of the peninsula.

FIGURE 2 Roman Empire and Via Appia in 312 BC. *Source*: Authors' drawing.

FIGURE 3 Roman empire and Via Appia in 238 BC. *Source*: Authors' drawing.

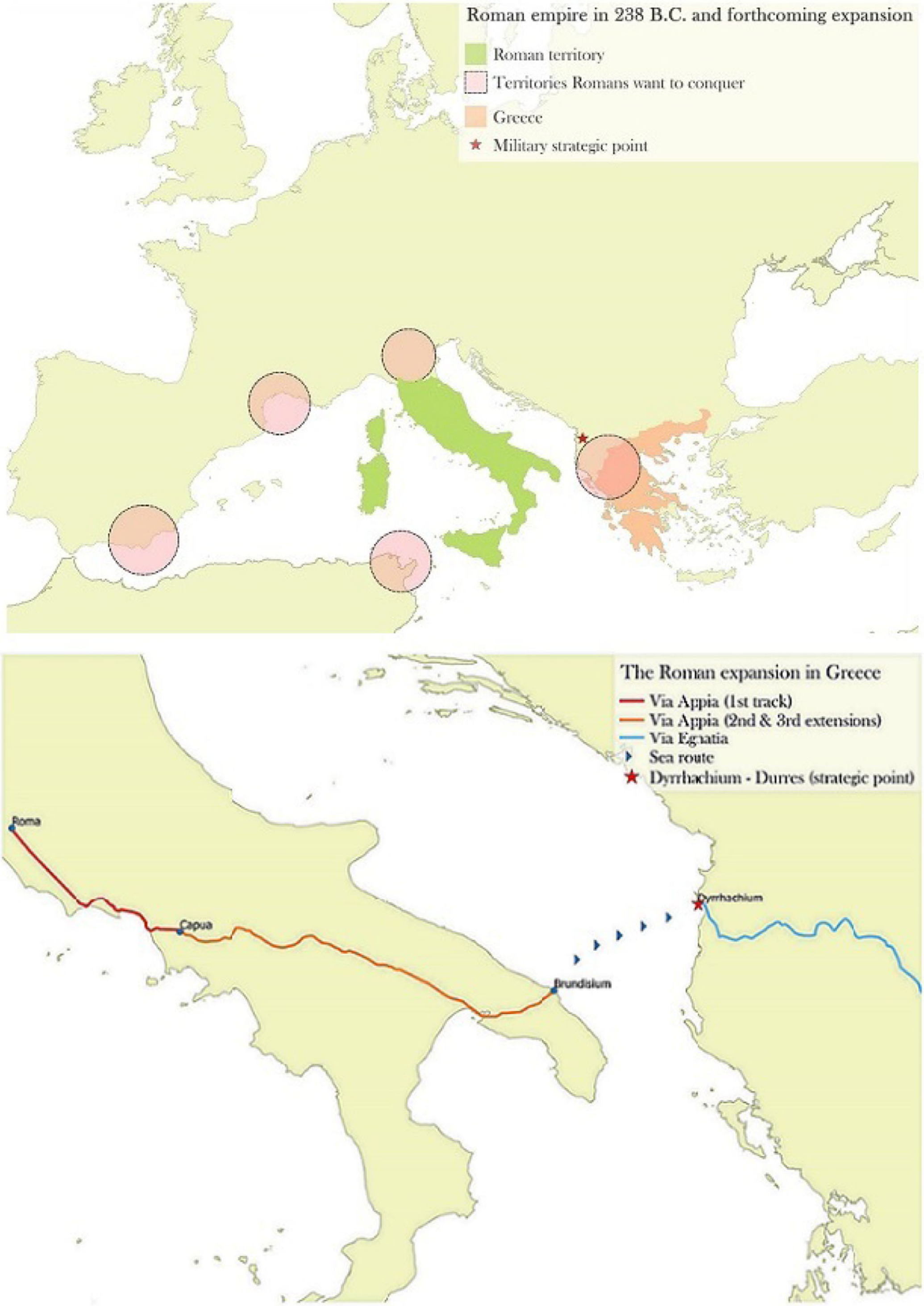

FIGURE 4 Romans' expansionist objectives and the conquest of Greece. *Source*: Authors' drawing.

FIGURE 5 The Via Annia. *Source*: Authors' drawing.

Nuceria (modern Nocera), Moranum (modern Morano), Cosentia (modern Cosenza), and Valentia (modern Vibo Valentia), all located to the West. However, despite the economic development and urbanization occurring in the eastern Calabrian coastline, where major trade centers like Sibari, Crotone, and Locri were situated, the Via Annia did not link these municipalities. The construction of the Via Annia reveals two primary insights: (1) the Roman approach to road building emphasized connecting strategic military points rather than forming a network among major urban centers, regardless of the road's size; (2) roads were conceived as a series of linear segments, the quickest and most straightforward way to connect two strategic locations.

Indeed, one of the remarkable engineering features of the Roman road network was the straightness of its roads. The Romans drew straight lines between two strategic locations and built the road as segments connected to one another. The first step in road construction involved marking as straight a path as possible with stakes and furrows, using sightlines as measuring tools.[23] To achieve the straightest line possible, the Romans built roads with steep slopes or passing through mountainous terrains (Margary, 1973). Even when variations in terrain morphology existed, the roads were still built in straight lines (see Bishop, 2014; Hindle, 1998; Welfare & Swan, 1995). Most nonmajor Roman roads exhibit some deviations from the main path, which were typically short and subject to a

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[23] The Romans preferred direct and straight roads, because with that outline it was easier to avoid ambuscades and human settlements. Moreover, straight roads were easier to secure (Gleason, 2013). As suggested by Poulter (2010) and as remarked by Bishop (2014), the Romans often did guard the beginning and end of the road; garrisons were typically placed at the top of a hill, and the road came along as the segment of a paved route connecting two garrisons. Von Hagen (1967), on the constitution of a mobile civilization throughout the continent, argues how this has been possible thanks to well-engineered and straight roads.

change in the degree of the layout. This is a distinguishing feature of Roman infrastructure from modern infrastructure.[24] Historians credit the straightness of Roman roads as the best rule for drawing an old historical infrastructure.[25]

4 | ROMAN ROADS, GEOGRAPHY, AND PRE-ROMAN CITIES

The construction of Roman roads has been attributed to spatial factors, including geography and market access. While historians have excluded a direct economic reason for the building of the consular roads, these factors may have played a role in the decision-making process. The morphology of the terrain was a critical consideration, as landform shapes both the spatial distribution of road infrastructure and economic activity. However, the relationship between geography and road-building is complicated, and some factors may be unobserved and correlated with both road construction and economic performance (Ramcharan, 2009).

The Romans developed primitive engineering techniques to deal with Italy's orography, which comprises 35% mountains, 42% hills, and 23% plains.[26] The investigation into the relationship between Roman roads and geography involved mapping elevation data from Istat and the polygon layer of the Italian territory using Figure 6. The layer of the Roman network was superimposed on the map, dividing roads into major (consular) and minor roads. The average altitude of each spatial unit was classified into five ordered equiproportional classes: (0–407 m), (407–814), (814–1221), (1221–1628), (1628–2035), and information on lakes and rivers was obtained using Corine Land Cover (CLC). The distribution of Roman roads among different elevation classes is fairly homogeneous, with the infrastructure even present in areas with higher elevation.[27] In central-southern Italy, there is a high concentration of Roman roads in the Apennines, the second mountain range in Italy, while in the North, the highest concentration of Roman roads is along the Po Valley, where the average elevation is lower. Overall, the graphical evidence suggests that the Romans approached the Italian territory in its complexity and variety, without leaving out any macro-area of the country, in its actual borders, without roads.

The construction of major/consular roads had Rome as the original hub and extended to all the necessary outposts to expand the Empire outside the borders of modern-day Italy. The positioning of the road in the mid-points, however, is still uncertain. To gain a better understanding of this, a thinner level of analysis was employed to examine how Romans approached the orography of the territory. The construction of roads primarily served to facilitate the movement of troops and vehicles (tanks) needed in military campaigns. Geography played a critical role in making this task harder. The proximity of roads to other civil infrastructure or pre-existing settlements traced those economic factors that went beyond the need to move the Empire's borders. Table 1 provides a list of information collected from different data sources and assembled for the analysis.

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[24] In light of this, Bishop (2014) refers to Roman roads as "*surveyed roads*" which originate from a geometric linear perspective in conceiving the network. Current roads are, instead, in the words of Bishop (2014), more linked to the "*line of desire*," since there is no geometric outline behind the planning of the network, but rather a preference to follow the shape of nature.

[25] The lines connecting two points in space, such as two main cities, are the focal point of the identification strategy of a strand of economic literature that started with the work of Banerjee et al. (2020). Straight lines capture the way the first modern transportation infrastructure was constructed, which by definition cannot be influenced by the actual level of development. Indeed, the infrastructure developed afterwards was built along historical routes. According to this reasoning, straight lines can be used as the optimal tool for guaranteeing access to infrastructure and to disentangle the areas that benefited from the infrastructure, due to their proximity to the line (treated areas), from those that did not, because of the distance (nontreated areas).

[26] The Romans resorted to deviations in roads only when major obstacles could not be overcome by building structures such as bridges, and whenever possible road supports, like embankments or dykes, or tunnels through hills and mountains (Richard, 2010). Their roads in the Alps and the Apennines had steep slopes and allowed the movement of pedestrians, horses, and wagons.

[27] The right part of Figure 6 zooms in on an exemplifying area of North-East Italy (i.e., the delimited rectangular area in the left part of the figure). The chosen area includes four different elevation zones, lakes and a stretch of Roman road that passes through lowlands and more elevated areas: the road does not circumnavigate the lake where the altitude is lower, but crosses a more elevated area.

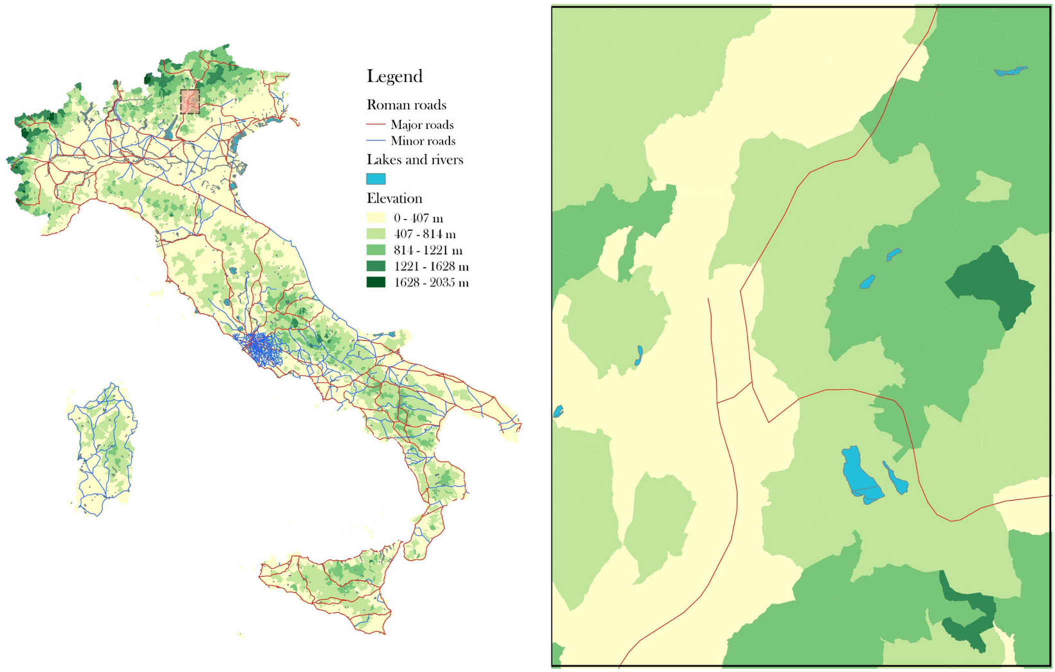

FIGURE 6 Roman roads and geography: position by elevation. *Source*: Authors' drawing from Istat data, Corine Land Cover data, McCormick et al. (2013). "Roman Road Network (version 2008)," DARMC Scholarly Data Series 2013-5.

In the following model, both geographical and human activities features that may affect the position of the network, are taken into account. The conditional correlation test is performed using 10 × 10 km grid cells as the unit of observation:

$$RR_i = \alpha_0 + \mathbf{G}_i\alpha_1 + \mathbf{MA}_i\alpha_2 + \varphi_p + u_i, \qquad (1)$$

where RR_i is the log-transformed measure of kilometers of major/consular roads;[28] while $\mathbf{G}_i$ denotes a matrix of various geographical measures, including physical controls, as in Dalgaard et al. (2022) and Flueckiger et al. (2022), such as $Ruggedness_i$, $Elevation_i$, $Slope_i$ that capture the terrain's physical harshness, height, and inclination. Other geographical measures reflect the terrain's agricultural value or end-of-use, such as *Pre-1500 agriculture suitability*$_i$, which measures the maximum calories yield of cropland before 1500. $Forest_i$ is a dummy variable that equals 1 if the grid cell is covered by forests or wooded vegetation, while *Low vegetation*$_i$ is a dummy variable that equals 1 if the cell is covered by pastures or scrubland.[29] Proximity to water is captured by *Distance from sea*$_i$ and *Distance from nearest waterway*$_i$, which measure the distance to the nearest seacoast and river, respectively. Direct market access measures in $\mathbf{MA}_i$ include *Distance from nearest harbor*$_i$ and *Distance from Rome*$_i$, which capture the proximity to a harbor or port and the distance from Rome, respectively. Additionally, information on the presence of settlements has been assembled from Pleiades: A Gazetteer of Past Places (Bagnall, 2016), and included in the model using the dummy variable *Pre-Roman amenities*$_i$, which equals 1 if a simple pre-Roman settlement or a settlement represented by civil infrastructure (amphitheatre, theatre, cemetery, sanctuary, bath, bridges, ports, forts) existed in the unit of analysis before the Romans.[30] Finally, NUTS3 provincial fixed effects (φ_p) are included in some specifications for

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[28] Both major and minor roads are tested in Section 5.1.

[29] The information, sourced from Goldewijk (2010), ISLSCP II Historical Land Cover and Land Use, 1700–1990, refers to the year 1700.

[30] For details see https://pleiades.stoa.org/help/data-structure.

TABLE 1 Variables and sources.

Variables	Definition	Years	Source	Available for
Major Roman roads	Length of major Roman roads in the grid cell (km)	117	Licio's (2021) elaboration from McCormick et al. (2013)	5111 10 × 10 km cells
All Roman roads	Length of all Roman roads in the grid cell (km)	117	Licio's (2021) elaboration from McCormick et al. (2013)	5111 10 × 10 km cells
Major Roman roads (residuals)	Length of major Roman roads in the grid cell (km) partialling out geography and market access	117	Authors' elaboration	5111 10 × 10 km cells
Railways	Length of current railways in the grid cell (km)	Modern	Authors' elaboration from Diva-GIS	5111 10 × 10 km cells
Motorways	Length of current motorways in the grid cell (km)	2009	Authors' elaboration from OpenStreetMap	5111 10 × 10 km cells
Mountain	Dummy variable: 1 if the mean elevation of the grid cell is ≥700 m	Time invariant	Authors' elaboration from Jarvis et al. (2008) "Hole-filled seamless SRTM data V4," International Centre for Tropical Agriculture (CIAT)	5104 10 × 10 km cells
Hill	Dummy variable: 1 if the mean elevation of the grid cell is ≥300 m, but <700 m	Time invariant	Authors' elaboration from Jarvis et al. (2008) "Hole-filled seamless SRTM data V4," International Centre for Tropical Agriculture (CIAT)	5104 10 × 10 km cells
Plain	Dummy variable: 1 if the mean elevation of the grid cell is <300 m	Time invariant	Authors' elaboration from Jarvis et al. (2008) "Hole-filled seamless SRTM data V4," International Centre for Tropical Agriculture (CIAT)	5104 10 × 10 km cells
Elevation	Average terrain elevation of the grid cell (m)	Time invariant	Authors' elaboration from Jarvis et al. (2008) "Hole-filled seamless SRTM data V4," International Centre for Tropical Agriculture (CIAT)	5104 10 × 10 km cells
Ruggedness	Average of the Terrain Ruggedness Index in the grid cell (hundred m)	Time invariant	Authors' elaboration from Nunn and Puga (2012)	5111 10 × 10 km cells
Slope	Average terrain slope in the grid cell (degrees)	Time invariant	Authors' elaboration from Jarvis et al. (2008) "Hole-filled seamless SRTM data V4," International Centre for Tropical Agriculture (CIAT)	5095 10 × 10 km cells

(Continues)

TABLE 1 (Continued)

Variables	Definition	Years	Source	Available for
Pre 1500 cropland suitability	Average of cropland suitability, as maximum calories yield, in the grid cell	Pre 1500	Authors' elaboration from Galor and Özak (2016)	5111 10 × 10 km cells
Post 1500 cropland suitability	Average of cropland suitability, as maximum calories yield, in the grid cell	Post 1500	Authors' elaboration from Galor and Özak (2016)	5111 10 × 10 km cells
Forest	Dummy variable: 1 if the grid cell was covered by forests or wooded vegetation	1700	Authors' elaboration from Goldewijk (2010) "ISLSCP II Historical Land Cover and Land Use, 1700-1990"	5111 10 × 10 km cells
Low vegetation	Dummy variable: 1 if the grid cell was covered by pastures or scrub lands	1700	Authors' elaboration from Goldewijk (2010) "ISLSCP II Historical Land Cover and Land Use, 1700-1990"	5111 10 × 10 km cells
Distance from sea	Distance from the nearest seacoast (km) to the grid cell's centroid	Time invariant	Authors' elaboration	5111 10 × 10 km cells
Distance from nearest waterway	Distance from the nearest river (km) to the grid cell's centroid	Time invariant	Authors' elaboration from OpenStreetMap	5111 10 × 10 km cells
Distance from nearest harbor	Distance from the nearest ancient harbor or port (km) to the grid cell's centroid	Ancient times	Authors' elaboration from de Graauw et al. (2013) "Geodatabase of Ancient Ports and Harbors"	5111 10 × 10 km cells
Distance from Rome	Distance from the city of Rome (km) to the grid cell's centroid	Time invariant	Authors' elaboration	5111 10 × 10 km cells
Pre-Roman amenities	Dummy variable: 1 if in the grid cell existed settlements, civil infrastructures or amenities (amphitheaters, theaters, cemeteries, sanctuaries, baths, bridges, ports, forts) before the Romans	Before 30 BC	Authors' elaboration from Pleiades	5111 10 × 10 km cells
Large municipality	Dummy variable: 1 if the grid cell had at least 1 municipality with more than 5000 inhabitants during the five centuries (1300–1861) before the construction of the current transport infrastructure	1300–1861	Authors' elaboration from Malanima (2015)	5111 10 × 10 km cells

Source: Authors' elaborations.

checking the robustness of coefficients' results, while u_i denotes the error term.[31]The analysis at the 10 × 10 km grid level is presented in Table 2, where the influence of geography and market access on the presence of Roman roads is measured.[32] The results are based on all 5111 grid cells in a first step. Table 2 shows that when only the orography of the terrain is considered (Models 2.1 and 2.3), ruggedness is the primary geographical variable significantly correlated with the presence of Roman roads, with elasticity coefficients of −0.043 and −0.041, respectively. The Shapley value regression analysis supports the idea that the topographic relief of the terrain played a significant role in determining the construction of the Roman road network. Table 2 shows that $Ruggedness_i$ and $Elevation_i$ contribute to the R^2 more than 25% and 28%, respectively, when only the orography of the land is considered. The distance from the sea and the suitability of terrains for cultivation account for 16.5% and 11.9% of the R^2, respectively. The results remain unchanged when NUTS3 level controls are included, as the coefficients in Model (2.3) are not significantly different from those in Model (2.1).

When different types of terrain are distinguished (Models (2.4), (2.5), and (2.6)), $Elevation_i$ and $Slope_i$ measures provide additional insights.[33] The elasticity of −0.515 for $Elevation_i$ indicates fewer kilometers of roads in challenging territories, with a smaller value for hilly lands and a nonsignificant coefficient for plain areas. The −1.355 slope elasticity confirms that Roman roads are sparser in more impervious areas.

Among the various geographical features, agriculture suitability has been an attractor in hill terrains, while the presence of low vegetation is a deterrent in plain areas. Proximity to sea and rivers, which are typically associated with the birth and growth of settlements (Bosker & Buringh, 2017; Buringh et al., 2012), do not play a significant role in the presence of Roman roads.

Integrating the territory's geography with market access measures (Models (2.2) and (2.7)), such as the presence of a harbor or the fact that all roads had Rome as a starting point, it emerges how the distance from a port is relevant in explaining the Roman road path; the central position of Rome, instead, emerges only in the model with fixed effects. Pre-Roman settlements test whether Roman roads were built near larger urban centers or favored the subsequent expansion of earlier settlements. Existing cities could become logistic bases for organizing troops and military camps, providing infrastructure sound in war campaigns. In this design set, the position of existing settlements and cities may have contributed to determining the trajectory of a road segment or its terminal point, which varied by construction stage. Also, the road may have generated agglomeration effects leading to the subsequent development of cities. $Pre\text{-}Roman\ amenities_i$ (any pre-Roman settlement, type of civil infrastructure, or amenity already present) are positively correlated with longer roads. The result is supported by the Shapley value: the civilization of ancient populations living in Italy before the Roman domination contributes to 70.5% of the R^2.

Given the possible selection effect, since not all 5111 grid cells have roads, Table 3 restricts the sample to the 1359 grid cells that host major Roman roads. The role of ruggedness and elevation is absent. When focusing on the intra-grid variance (Models (3.3) and (3.4)), the grid cells with higher slopes, instead, have fewer kilometers of roads. Results on the quality of the land and market access (Models 3.2 and 3.4) are all confirmed, with a weaker role played by the harbor distance. The presence of ancient urbanization accounts for nearly 88% of the R^2.[34]

Overall, the results confirm the evidence in Figure 6, showing that the construction of Roman roads is linked to geography but not limited by it. Roman roads are present in all types of terrains. Once a grid cell was selected to

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[31] For all specifications, Conley standard errors have been computed and calculated with a spatial cutoff of 150 km. Results are confirmed for shorter and longer distances.

[32] The selection of the sole grid cells with Roman roads is accounted for in Table 3.

[33] Cells are classified according to three terrain zones: mountainous (if elevation is equal to or more than 700 m); hilly (if elevation is less than 700 m, but equal to or more than 300 m); plain (if elevation is less than 300 m).

[34] The inclusion of NUTS3 fixed effects controls for the territorial heterogeneity at the province level. This reduces the contribution to the R^2 of both geographical and urbanization variables since the explanatory power of the fixed parameters. The Shapley value regression analysis shows that when fixed effects are included in the model pre-Roman amenities contribute to 33.8% to the R^2. Fixed effects, instead, are responsible for more than 57% of the R^2. Results are available upon request.

TABLE 2 Determinants of constructing major Roman roads (all cells).

Dependent variable: major Roman roads in km (log)	(2.1) Total	(2.2) Total	(2.3) Total	(2.4) Mountain	(2.5) Hill	(2.6) Plain	(2.7) Total
Ruggedness (log)	−0.043**	−0.045**	−0.041**	0.084	−0.047	−0.063*	−0.045**
	(0.019) [25.5]	(0.018) [6.7]	(0.019)	(0.082)	(0.094)	(0.037)	(0.018)
Elevation (log)	−0.019	−0.036*	−0.105***	−0.515***	−0.243***	0.006	−0.092***
	(0.030) [28.4]	(0.019) [6.6]	(0.010)	(0.084)	(0.054)	(0.039)	(0.012)
Slope (log)	0.077*	0.040	0.096**	−1.355*	0.156	0.080*	0.078**
	(0.042) [2.5]	(0.030) [0.2]	(0.041)	(0.732)	(0.151)	(0.041)	(0.037)
Agriculture suitability pre 1500 (log)	0.018**	0.003	0.041***	0.019**	0.117***	0.016	0.031***
	(0.007) [11.9]	(0.013) [1.7]	(0.008)	(0.008)	(0.032)	(0.023)	(0.006)
Forest (dummy)	0.027	0.037	0.067	0.250***	0.114	−0.042	0.078
	(0.064) [2.0]	(0.033) [0.6]	(0.071)	(0.031)	(0.177)	(0.049)	(0.069)
Low vegetation (dummy)	−0.086*	−0.102***	−0.073**	0.095***	0.012	−0.075***	−0.063*
	(0.050) [9.5]	(0.038) [2.5]	(0.034)	(0.035)	(0.094)	(0.016)	(0.034)
Distance from sea (log)	−0.033	0.016	0.029	0.096	−0.110	0.052*	0.036*
	(0.034) [16.5]	(0.027) [2.4]	(0.025)	(0.098)	(0.106)	(0.028)	(0.022)
Distance from nearest waterway (log)	0.019	−0.013	−0.023	−0.004	−0.044	−0.016	−0.016
	(0.018) [3.8]	(0.017) [0.5]	(0.023)	(0.036)	(0.033)	(0.042)	(0.020)
Distance from nearest harbor (log)		−0.105**					−0.114***
		(0.043) [7.7]					(0.040)
Distance from Rome (log)		0.049					−0.435**
		(0.109) [0.6]					(0.190)
Pre-Roman amenities (dummy)		0.684***					0.638***
		(0.078) [70.5]					(0.076)
φ_p	No	No	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5095	5095	5095	1371	1304	2420	5095
Adjusted R^2	0.201	0.267	0.269	0.196	0.253	0.336	0.324

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 km. Results are confirmed for shorter and longer distances. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels: $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

TABLE 3 Determinants of major Roman roads (non-zero cells).

Dependent variable: major Roman roads in km (log)	(3.1)	(3.2)	(3.3)	(3.4)
Ruggedness (log)	−0.016	−0.037	−0.052	−0.056
	(0.033) [10.5]	(0.036) [1.9]	(0.057)	(0.060)
Elevation (log)	0.015	0.014	0.036	0.037
	(0.047) [11.5]	(0.046) [1.2]	(0.071)	(0.071)
Slope (log)	0.056	−0.005	−0.226**	−0.207*
	(0.117) [0.6]	(0.132) [0.0]	(0.109)	(0.121)
Agriculture suitability pre 1500 (log)	0.031***	0.029	0.065***	0.066***
	(0.010) [23.1]	(0.021) [1.6]	(0.022)	(0.023)
Forest (dummy)	−0.069	−0.077	0.030	0.037
	(0.063) [9.7]	(0.071) [1.0]	(0.057)	(0.067)
Low vegetation (dummy)	−0.035	−0.040	−0.015	−0.030
	(0.046) [2.9]	(0.072) [0.3]	(0.063)	(0.081)
Distance from sea (log)	0.031	0.055***	0.089***	0.101**
	(0.021) [36.5]	(0.020) [4.7]	(0.032)	(0.039)
Distance from nearest waterway (log)	0.015	−0.005	−0.020	−0.003
	(0.025) [5.3]	(0.023) [0.4]	(0.039)	(0.033)
Distance from nearest harbor (log)		−0.038		−0.103*
		(0.037) [1.0]		(0.054)
Distance from Rome (log)		0.018		−0.419**
		(0.046) [0.4]		(0.180)
Pre-Roman amenities (dummy)		0.500***		0.515***
		(0.091) [87.6]		(0.102)
φ_p	No	No	Yes	Yes
Constant	Yes	Yes	Yes	Yes
Observations	1359	1359	1359	1359
Adjusted R^2	0.682	0.695	0.682	0.697

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 kilometers. Results are confirmed for shorter and longer distances. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels: $^*p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

host a road, the role of geography vanished, and more urban and market access factors became relevant in explaining the length of the network. This paper's first result will be used to investigate the link between old and new infrastructure in the following section, which is one main goal of the paper: giving robust evidence of what can be seen as a first stage in an instrumental variable strategy to overcome the limits of the endogeneity of modern transport infrastructure.

5 | OLD AND MODERN INFRASTRUCTURE

This section investigates the relationship between the historical Roman road network and current transport infrastructure in Italy, specifically railways and motorways, by exploring the factors behind their linkage.[35] Cultural and landscape conditions are found to determine why new infrastructure may be related to the ancient one, particularly in terms of the birth and development of economic centers.[36] City location, on the other hand, has been linked to the presence of road infrastructure, indicating a nonrandom process (Bosker et al., 2008; Bosker & Buringh, 2017). Additionally, the cost of transport infrastructure projects is directly affected by geography. The presence of old infrastructure facilitates the construction of new ones, especially when the landform creates construction difficulties.

The detailed units of analysis employed in this study allow for an integrated view of Italy's geography and a consideration of how modern infrastructure has been designed at the national level. The needs expressed by local administrative authorities, such as regions and provinces, are taken into account using controls at the NUTS3 level. Moreover, provinces provide the highest within-country variance and pinpoint control for those historical legacies that followed the Roman Empire's collapse.[37]

The model specification, presented in Equation (2),

$$I_i = \beta_0 + \beta_1 RR_i + \mathbf{G}_i\beta_2 + \mathbf{MA}_i\beta_3 + \varphi_p + u_i, \tag{2}$$

involves regressing measures of modern infrastructure, specifically railways and motorways, on the measure of Roman roads. The dependent variable, I_i, represents the log transformation of the two measures in kilometers. The two different transport systems are considered due to how transport infrastructure developed in Italy, with railways dating back to 1839 and motorways to 1924. $\mathbf{G}_\text{i}$ is the matrix of the discussed geographical measures, with agriculture suitability referring to post-1500, while $\mathbf{MA}_\text{i}$ is the matrix of market access variables. *Pre-Roman amenities*$_i$ are replaced by the binary variable *Large municipality*$_i$, accounting for the urbanization of Italian cities before the construction of modern infrastructure. This variable aims to mimic the role that pre-Roman settlements, civil infrastructures or amenities had in controlling urban development before the expansion of Roman roads. The dummy variable takes the value of 1 if the grid cell i had at least one municipality with more than 5000 inhabitants between 1300 and 1861, before the new transport network was built.[38] The measure intends to capture the recursive effect from the old infrastructure to the birth and growth of cities and then back to the new transport infrastructure provision. Finally, NUTS3 provincial fixed effects φ_p complete the model specification, while u_i denotes the error term.[39]

Table 4 displays the results of the model applied to the grid cells, which contain segments of railways (Models (4.1) to (4.4)) or motorways (Models (4.5) to (4.8)). Major (consular) roads are positively correlated with current infrastructure, more so in the case of motorways, with an elasticity of I_i to RR_i ranging from 0.30 to 0.34 for railways (without and with provincial controls, respectively) and 0.36 to 0.39 for motorways. The effect of geography (with or without provincial controls) is limited to certain variables, such as *Distance from sea*$_i$ for railways and *Ruggedness*$_i$ and *Low vegetation*$_i$ for motorways. The development of urban municipalities before the unification of Italy is associated with a higher quantity of current infrastructure when including market access measures, with coefficients of 0.48 and 0.39 for railways and motorways, respectively. Railways and motorways serve the

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[35] For an analysis on the intersection between the Roman road network and the Italian railway and motorway system see Supporting Information: Appendix B.

[36] Several contributions (see Garcia-López et al. (2015) among others) stress that motorways are not located at random and argue in favor of the location of cities as the main driver of modern road infrastructure.

[37] An interesting strand of the literature focuses on the role of the social capital in Italy, exploiting the heterogeneity that originated from the events that followed the collapse of the Roman Empire (Guiso et al., 2004).

[38] Data come from Malanima (2015): municipalities are considered as cities if their population was over 5000 inhabitants.

[39] Conley standard errors are computed for all specifications with a spatial cutoff of 150 kilometers. Results are confirmed for shorter and longer distances.

TABLE 4 Determinants of modern transport infrastructure (non-zero cells).

	Railways				Motorways			
Dependent variable: Current infrastructure in km (log)	**(4.1)**	**(4.2)**	**(4.3)**	**(4.4)**	**(4.5)**	**(4.6)**	**(4.7)**	**(4.8)**
Major RR_i (log)	0.301***	0.273***	0.336***	0.298***	0.362***	0.340***	0.393***	0.362***
	(0.023) [91.0]	(0.023) [65.9]	(0.022)	(0.022)	(0.020) [88.5]	(0.012) [73.4]	(0.029)	(0.030)
Ruggedness (log)	−0.054	−0.041	−0.067	−0.048	−0.123**	−0.096*	−0.163*	−0.122
	(0.045) [2.1]	(0.050) [1.5]	(0.046)	(0.047)	(0.056) [4.1]	(0.058) [2.9]	(0.090)	(0.103)
Elevation (log)	0.060	0.047	0.071	0.080	0.093	0.077	0.100	0.076
	(0.046) [1.9]	(0.053) [1.5]	(0.062)	(0.057)	(0.083) [1.5]	(0.089) [1.1]	(0.137)	(0.142)
Slope (log)	−0.146	−0.329	−0.110	−0.290	−0.045	−0.322	−0.107	−0.370
	(0.274) [0.1]	(0.274) [0.2]	(0.307)	(0.322)	(0.654) [0.0]	(0.643) [0.1]	(0.470)	(0.521)
Agriculture suitability post 1500 (log)	0.019	0.004	0.000	−0.014	−0.002	−0.006	−0.016	−0.029
	(0.015) [0.1]	(0.018) [0.0]	(0.027)	(0.028)	(0.027) [0.0]	(0.025) [0.0]	(0.032)	(0.030)
Forest (dummy)	−0.083	−0.052	−0.156*	−0.110	−0.091	−0.053	−0.225	−0.217
	(0.067) [0.6]	(0.075) [0.3]	(0.088)	(0.082)	(0.078) [0.4]	(0.109) [0.2]	(0.165)	(0.142)
Low vegetation (dummy)	0.040	0.034	0.031	0.057	−0.181***	−0.175**	−0.187***	−0.131*
	(0.035) [0.2]	(0.045) [0.1]	(0.036)	(0.036)	(0.063) [3.6]	(0.085) [3.2]	(0.067)	(0.074)
Distance from sea (log)	0.058***	0.072***	0.116**	0.093**	0.006	0.009	0.126	0.157
	(0.003) [3.6]	(0.025) [3.8]	(0.046)	(0.045)	(0.040) [0.9]	(0.042) [1.0]	(0.111)	(0.113)
Distance from nearest waterway (log)	0.023	0.001	0.022	0.028	0.032	0.027	0.049	0.044
	(0.018) [0.4]	(0.022) [0.2]	(0.030)	(0.029)	(0.034) [0.9]	(0.036) [0.6]	(0.057)	(0.058)
Distance from nearest harbor (log)		−0.008		−0.058		0.037		−0.078
		(0.039) [0.6]		(0.070)		(0.035) [0.6]		(0.064)

(Continues)

TABLE 4 (Continued)

	Railways				Motorways			
Dependent variable: Current infrastructure in km (log)	**(4.1)**	**(4.2)**	**(4.3)**	**(4.4)**	**(4.5)**	**(4.6)**	**(4.7)**	**(4.8)**
Distance from Rome (log)		0.002		−0.136		0.019		0.421***
		(0.035) [0.1]		(0.142)		(0.050) [0.2]		(0.075)
Large municipality (dummy)		0.352***		0.479***		0.305***		0.386***
		(0.040) [25.7]		(0.053)		(0.080) [16.8]		(0.112)
φ_p	No	No	Yes	Yes	No	No	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,236	2,236	2,236	2,236	907	907	907	907
Adjusted R^2	0.747	0.753	0.749	0.758	0.684	0.688	0.675	0.682

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 kilometers. Results are confirmed for shorter and longer distances. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels:

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

connectivity of larger cities, where being connected to a major Roman road or hub is a determining factor for smaller cities to become larger centers (Bosker et al., 2008; Bosker et al., 2013).[40] Recent contributions on the geographical location of cities (Bosker & Buringh, 2017; Bosker et al., 2013; Michaels & Rauch, 2018) highlight the founding and growth of cities as a driving force behind the need for new infrastructure. The reported results indicate an independent effect of pre-existing urban development and old infrastructure on the current one, with consistently significant coefficients on both variables.

The Shapley value regression analysis, performed on the models of Table 4, controls for multicollinearity and evaluates the importance of predictors. The results demonstrate that Roman roads have 2.5- and 4.3-times greater role than urban municipalities in explaining the quantity of modern railways and motorways, respectively. Both variables contribute more than 90% to the R^2, while all other geographical factors play a residual role. The Shapley values are confirmed when NUTS3 fixed effects are included in the models, with, clearly, a lower contribution to the R^2: Roman roads are still the main predictor for the modern transport infrastructure, accounting for 44% and 48% of the R^2 for railways and motorways, respectively. Together with urbanization, Roman roads account for 64% and 60% of the variance of railways and motorways.[41]

Estimations for all Italian grid cells, with and without railways or motorways, are available in Supporting Information: Table A1 of Appendix A. The results are consistent with the evidence presented above, highlighting the predominance of Roman roads in determining the presence of infrastructure and how their legacy played an important role in plain zones.

5.1 | Robustness checks

The aim of this section is to assess the reliability and relevance of the Roman road index (RR_i) by testing the impact of variations in the definition of the old infrastructure measure and the set of territorial units included in the analysis. The first set of robustness checks focuses on the complete old infrastructure, which includes minor roads that were constructed to connect pre-Roman settlements or amenities to major roads, that in some cases were as important as consular roads (Filiasi, 1792), and enhance the connectedness of the entire network. Including minor roads increases the kilometers of roads considered, re-scaling the RR_i variable used in Equation (2) and enlarging the number of grid cells used to determine the effect of geography and market access on the old infrastructure, as in Equation (1). The results in Table 5 indicate that when minor Roman roads are considered (Models (5.1)–(5.4)), the positive correlation between old and current infrastructure holds for both railways and motorways, with slightly larger coefficients in both equations compared to the sole major roads specifications. Accounting for minor roads (Models (5.5) and (5.6)) refines the role of geography and shows that rougher territories have less Roman roads, but a steeper terrain (slope) is associated with more kilometers of the old infrastructure. The role of Rome as the central node of the network is amplified, and the positive association with the presence of pre-Roman amenities is confirmed.

Once again, the Shapley value regression analysis confirms the predominance of the Roman infrastructure in explaining the variance of the modern infrastructure (more than 70% of the R^2).

Table 6 returns to a measure of only major (consular) Roman roads ($\tilde{RR}_i$), which is now orthogonal to both geography and market access measures. This is done by using the residuals of Equation (1) as in Model (3.4) of Table 3. The estimates' precision is checked for possible spatial effects within 150 km using Conley standard errors and bootstrap standard errors.[42] The results show that the landform, captured by ruggedness, continues to play a

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[40] This validates the choice of including urban centers located nearby a major (consular) Roman road.

[41] Results are available upon request.

[42] As an estimator, the generated measure of Roman roads has additional sampling variance that needs to be taken into account when calculating the variance of final parameter estimates. Bootstrap standard errors control for that.

TABLE 5 Robustness checks: all Roman roads (non-zero cells).

Dependent variable: Transport infrastructure in km (log)	Railways		Motorways		All RR	
	(5.1)	(5.2)	(5.3)	(5.4)	(5.5)	(5.6)
All RR_i (log)	0.299***	0.320***	0.368***	0.397***		
	(0.019) [73.4]	(0.017)	(0.029) [78.4]	(0.035)		
Ruggedness (log)	−0.024	−0.034	−0.076	−0.105	−0.087*	−0.104**
	(0.045) [0.9]	(0.045)	(0.049) [2.0]	(0.081)	(0.046) [3.5]	(0.048)
Elevation (log)	0.030	0.070	0.053	0.050	0.055	0.036
	(0.045) [1.0]	(0.052)	(0.078) [0.8]	(0.120)	(0.048) [1.8]	(0.060)
Slope (log)	−0.400	−0.396	−0.610	−0.632	0.013	0.211*
	(0.286) [0.2]	(0.350)	(0.721) [0.2]	(0.618)	(0.157) [0.1]	(0.120)
Agriculture suitability post 1500 (log)	0.004	−0.019	−0.003	−0.023		
	(0.016) [0.0]	(0.024)	(0.030) [0.0]	(0.032)		
Forest (dummy)	0.001	−0.055	0.007	−0.156	−0.062	0.077
	(0.078) [0.2]	(0.075)	(0.089) [0.2]	(0.127)	(0.050) [0.7]	(0.126)
Low vegetation (dummy)	0.034	0.083	−0.133	−0.065	−0.022	−0.037
	(0.048) [0.1]	(0.053)	(0.095) [2.4]	(0.074)	(0.062) [0.1]	(0.068)
Distance from sea (log)	0.070***	0.092*	0.025	0.161	0.049**	0.102***
	(0.026) [2.9]	(0.052)	(0.025) [0.9]	(0.104)	(0.024) [3.1]	(0.033)
Distance from nearest waterway (log)	−0.016	0.009	0.018	0.031	0.022	0.059*
	(0.025) [0.3]	(0.028)	(0.033) [0.3]	(0.055)	(0.025) [2.5]	(0.035)
Distance from nearest harbor (log)	−0.013	−0.079	0.003	−0.089	−0.074	−0.085*
	(0.034) [0.5]	(0.071)	(0.039) [0.4]	(0.067)	(0.049) [4.0]	(0.044)
Distance from Rome (log)	0.115**	−0.015	0.137***	0.482***	−0.161***	−0.843***
	(0.046) [1.2]	(0.116)	(0.036) [1.8]	(0.055)	(0.053) [16.3]	(0.250)
Large municipality (dummy)	0.334***	0.422***	0.254***	0.327***		
	(0.027) [19.4]	(0.052)	(0.080) [12.6]	(0.114)		
Agriculture suitability pre 1500 (log)					0.015	0.059***
					(0.026) [0.6]	(0.021)
Pre-Roman amenities (dummy)					0.571***	0.628***
					(0.042) [67.4]	(0.035)
φ_p	No	Yes	No	Yes	No	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2236	2236	907	907	2076	2076
Adjusted R^2	0.762	0.767	0.700	0.697	0.719	0.728

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 km. Results are confirmed for shorter and longer distances. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels: $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

TABLE 6 Robustness checks: major Roman roads as residuals of Model (3.4) of Table 3 (non-zero cells).

	Railways				Motorways			
Dependent variable: Current infrastructure in km (log)	**(6.1)**	**(6.2)**	**(6.3)**	**(6.4)**	**(6.5)**	**(6.6)**	**(6.7)**	**(6.8)**
Major $\tilde{RR}_i$ (log)	0.141***	0.141***	0.272***	0.272***	0.219***	0.219***	0.352***	0.352***
	(0.030) [39.2]	(0.017) [39.2]	(0.024)	(0.025)	(0.037) [51.8]	(0.034) [51.8]	(0.027)	(0.042)
Ruggedness (log)	−0.061	−0.061**	−0.060	−0.060*	−0.114***	−0.114**	−0.132	−0.132**
	(0.045) [3.1]	(0.031) [3.1]	(0.047)	(0.036)	(0.057) [5.2]	(0.053) [5.2]	(0.093)	(0.067)
Elevation (log)	0.045	0.045	0.090	0.090*	0.090	0.090	0.088	0.088
	(0.050) [2.0]	(0.038) [2.0]	(0.058)	(0.048)	(0.091) [2.2]	(0.064) [2.2]	(0.132)	(0.091)
Slope (log)	−0.261	−0.261	−0.369	−0.369	−0.205	−0.205	−0.468	−0.468
	(0.304) [0.2]	(0.318) [0.2]	(0.315)	(0.365)	(0.548) [0.1]	(0.674) [0.1]	(0.437)	(0.775)
Agriculture suitability post 1500 (log)	−0.017	−0.017	0.005	0.005	−0.019	−0.019	−0.002	−0.002
	(0.018) [0.1]	(0.025) [0.1]	(0.031)	(0.029)	(0.027) [0.1]	(0.042) [0.1]	(0.031)	(0.052)
Forest (dummy)	−0.030	−0.030	−0.088	−0.088	−0.003	−0.003	−0.195	−0.195
	(0.073) [0.3]	(0.068) [0.3]	(0.081)	(0.094)	(0.096) [0.3]	(0.110) [0.3]	(0.162)	(0.168)
Low vegetation (dummy)	−0.056	−0.056	0.053	0.053	−0.204*	−0.204**	−0.128*	−0.128
	(0.052) [0.3]	(0.055) [0.3]	(0.041)	(0.074)	(0.108) [5.6]	(0.101) [5.6]	(0.077)	(0.147)
Distance from sea (log)	0.074**	0.074***	0.116**	0.116***	0.038	0.038	0.186	0.186**
	(0.034) [5.3]	(0.028) [5.3]	(0.046)	(0.043)	(0.036) [2.4]	(0.042) [2.4]	(0.117)	(0.095)
Distance from nearest waterway (log)	−0.011	−0.011	0.025	0.025	0.020	0.020	0.040	0.040
	(0.020) [0.3]	(0.019) [0.3]	(0.030)	(0.027)	(0.038) [0.8]	(0.034) [0.8]	(0.061)	(0.048)
Distance from nearest harbor (log)	−0.046	−0.046	−0.093	−0.093	−0.048	−0.048	−0.126*	−0.126
	(0.047) [1.4]	(0.029) [1.4]	(0.072)	(0.059)	(0.053) [1.3]	(0.046) [1.3]	(0.068)	(0.105)

(Continues)

TABLE 6 (Continued)

Dependent variable: Current infrastructure in km (log)	Railways				Motorways			
	(6.1)	(6.2)	(6.3)	(6.4)	(6.5)	(6.6)	(6.7)	(6.8)
Distance from Rome (log)	−0.010	−0.010	−0.265*	−0.265*	0.025	0.025	0.304	0.304
	(0.039) [0.1]	(0.038) [0.1]	(0.143)	(0.151)	(0.051) [0.4]	(0.062) [0.4]	(0.388)	(0.377)
Large municipality (dummy)	0.459***	0.459***	0.499***	0.499***	0.383***	0.383***	0.408***	0.408***
	(0.048) [47.7]	(0.046) [47.7]	(0.055)	(0.053)	(0.091) [29.7]	(0.083) [29.7]	(0.108)	(0.098)
φ_p	No	No	Yes	Yes	No	No	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2236	2236	2236	2236	907	907	907	907
Adjusted R^2	0.742	0.742	0.754	0.754	0.669	0.669	0.677	0.677

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. For Specification (1), (3), (5), and (7) Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 km. Results are confirmed for shorter and longer distances. For Specification (2), (4), (6) and (8) bootstrap standard errors (10,000 replications) are reported in parentheses. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels:

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

TABLE 7 Robustness checks: no cells surrounding Rome (distance >250 *km*).

Dependent variable: Transport infrastructure in km (log)	Railways		Motorways		Major RR	
	(7.1)	(7.2)	(7.3)	(7.4)	(7.5)	(7.6)
Major RR_i (log)	0.286***	0.315***	0.336***	0.365***		
	(0.022) [67.3]	(0.016)	(0.026) [68.9]	(0.024)		
Ruggedness (log)	−0.024	−0.025	−0.051	−0.057	−0.004	−0.024
	(0.047) [1.2]	(0.051)	(0.043) [2.2]	(0.064)	(0.023) [0.9]	(0.045)
Elevation (log)	0.025	0.053	−0.001	0.006	−0.019	0.005
	(0.049) [0.8]	(0.063)	(0.073) [0.6]	(0.100)	(0.049) [1.1]	(0.077)
Slope (log)	−0.269	−0.187	0.196	0.024	0.122	−0.168
	(0.213) [0.1]	(0.326)	(0.396) [0.2]	(0.118)	(0.143) [0.2]	(0.116)
Agriculture suitability post 1500 (log)	−0.003	−0.014	−0.004	−0.029		
	(0.026) [0.1]	(0.029)	(0.028) [0.1]	(0.040)		
Forest (dummy)	−0.058	−0.089	0.004	−0.138	−0.055	−0.105
	(0.116) [0.4]	(0.100)	(0.140) [0.3]	(0.175)	(0.041) [0.9]	(0.064)
Low vegetation (dummy)	0.033	0.032**	−0.140*	−0.048	0.008	0.032
	(0.028) [0.2]	(0.015)	(0.075) [2.5]	(0.157)	(0.060) [0.1]	(0.076)
Distance from sea (log)	0.082**	0.125**	0.051	0.209	0.079***	0.140***
	(0.032) [3.3]	(0.050)	(0.052) [0.8]	(0.148)	(0.023) [6.5]	(0.055)
Distance from nearest waterway (log)	−0.003	0.048*	0.038	0.091	0.007	0.021
	(0.029) [0.3]	(0.028)	(0.047) [0.7]	(0.064)	(0.027) [0.4]	(0.037)
Distance from nearest harbor (log)	−0.007	−0.078	0.018	−0.124	−0.011	−0.102*
	(0.052) [0.5]	(0.091)	(0.061) [0.4]	(0.086)	(0.038) [0.6]	(0.061)
Distance from Rome (log)	−0.136	−0.285	0.160	0.702	0.247*	0.500
	(0.180) [0.3]	(0.346)	(0.246) [1.0]	(1.160)	(0.127) [2.7]	(0.454)
Large municipality (dummy)	0.350***	0.520***	0.390***	0.563***		
	(0.062) [25.7]	(0.077)	(0.093) [22.6]	(0.108)		
Agriculture suitability pre 1500 (log)					0.060***	0.088***
					(0.020) **[4.5]**	(0.018)
Pre-Roman amenities (dummy)					0.557***	0.565***
					(0.060) **[82.1]**	(0.070)
φ_p	No	Yes	No	Yes	No	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1669	1669	657	657	1005	1005
Adjusted R^2	0.756	0.763	0.690	0.690	0.731	0.727

Note: All log-transformed variables are indicated with (log). φ_p represents NUTS3 province fixed effects. Conley standard errors are reported in parentheses and calculated with a spatial cutoff of 150 kilometers. Results are confirmed for shorter and longer distances. Normalized Shapley values are reported in square brackets. Asterisks denote significance levels: $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

role in deterring the quantity of motorways, less in the case of railways. The size of the other effects (old infrastructure and large municipalities) are comparable with the results discussed above. The use of a measure that partials out geographical and urban factors ($R\tilde{R}_i$) does not vary the importance that the Roman infrastructure has in explaining the modern one. Roman roads are still the main predictor for motorways and account for 52% of the R^2. For railways, instead, the contribution of large municipalities slightly exceeds the one of Roman roads: 48% and 39%, respectively.

The last set of robustness checks deals with the fact that all consular roads have a common starting point, Rome, which determines a concentration of the old infrastructure in the territories nearby the capital. The specifications in Table 7 are obtained by excluding all grid cells for which the distance from Rome is less than 250 km. The results of Equation (1) (Models (7.5) and (7.6)) show that when moving from Rome, the Italian landform changes, including hills and mountains, and the coefficients of geographical variables are not statistically significant, indicating that the more challenging geography did not impede the historical infrastructure construction. The discussion is similar when looking at the results of Equation (2) (Models (7.1) to (7.4)): the old infrastructure and the presence of a municipality are the main determinants of the quantity of both railways and motorways, and the size of the coefficients in both dependent outcomes is robust to the various controls. Interestingly, the results on the coefficients of the main determinants of interest do not change, while the variable *Distance from Rome*$_i$ loses all its explanatory power. The results of the Shapley value regression analysis are confirmed for all specifications of Table 7.

6 | CONCLUDING REMARKS

This paper provides novel evidence on the long-term impact of the Roman Empire on the modern-day road and railway system in Italy, demonstrating how the Roman road network has had a persistent effect on the present-day infrastructure.

The study focuses on the consular Roman road network, which was built with a linear design between strategic points, and shows that it has played a critical role in shaping the current motorway and railway networks. The paper uses detailed data at the grid cell level (10 × 10 km) and combines geographical, historical, and more urban and economic variables to investigate the legacy of Roman roads on the modern infrastructure, providing an analysis in two steps. First, the study observes the effect of confounding variables on the construction of Roman roads, revealing that geography affected the building of the consular road network without limiting it. The analysis shows that Roman roads conformed more to a linear shape than to the most geographically advantageous layout and once a grid cell was selected to host a road, the role of geography in determining the length of the network becomes secondary leaving space to more urban and economic factors. Second, the analysis tests the effect of Roman roads on current railways and motorways in Italy and finds a significant positive impact of the integrated ancient Roman road network on existing infrastructure.

The paper's contributions are therefore twofold. Firstly, it builds on the first stage of an instrumental variable empirical strategy, which involves establishing the exogeneity and relevance of the instrument, demonstrating the validity of the Roman road system as an instrument for modern-day infrastructure investments. Secondly, the study provides a methodological framework for analyzing the properties of historical infrastructures. The study's results suggest that areas with a denser Roman road network are more likely to have denser road and railway infrastructure today since Roman roads shaped the Italian landscape, making the construction of current roads less costly. The mechanisms that have been highlighted in the literature are the role of Roman roads in fostering accessibility (Bosker & Buringh, 2017) and urban development (Bosker et al., 2013; Michaels & Rauch, 2018). The results of the present paper are robust to various controls and to the inclusion of minor (secondary) roads in the analysis, giving further detailed evidence on the persistence of ancient transportation infrastructure on modern ones.

The study's findings have important implications for policymakers and researchers interested in using historical infrastructure as a mean of identifying the causal impact of infrastructure investments on economic outcomes.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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