Land transport in mountainous regions in the Roman Empire: Network analysis in the case of the Alps and Pyrenees

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Abstract

This paper attempts to analyse the land transport in Roman times in mountainous areas, taking into account the most feasible location for the road infrastructures as well as the conditions for different means of transport. With the use of different GIS applications such as LCP (Low Cost Paths) and Network analysis, the study aims to recognise the time, effort and cost that was involved in crossing important mountainous barriers such as the Pyrenees and the Alps. In spite of the lack of an economic return, the Roman Empire invested a lot of resources in building complex infrastructures up in mountainous regions. This paper addresses the reasons behind such an economic effort.

Keywords

Land transport; Roman; Network analysis; GIS; Gradient; *Portoria*; *Statio*

Introduction

Since antiquity, land transport has been one of the most complex means of transport due to land surface conditions. Mountains have always been the main obstacle for land transport, and cultures have tended to avoid them rather than prevail over them. Rome was the first civilization to overcome these obstacles by building steep slopes and small tunnels (Leveau, 2008). The main challenge for the Western Roman Empire was to raise special finance to connect the whole of the Roman Empire with the Pyrenees and the Alps (Leveau and Palet, 2010). Rome created a network of roads that was still remained in use during in Medieval and Modern times with minor changes.

Until the 19th century there were few changes in Europe in terms of infrastructure, with little advance in terms of technology, and a lack of interest in overcoming the mountains. The reason for considering mountains as peripheral areas is that mountains are excellent natural borders between States, as in the case of large rivers. They become sturdy frontiers without any changes in their situation. Mountains are an important source of minerals, snow, wood and grassland, enough resources to feed a relatively low density population. Nevertheless, the existing borders do not restrict their permeability into mountainous regions.

The mid-nineteenth century railway revolution also affected mountainous areas with the development of the “cremaillere” or rack railway technology that manages to overcome gradients of 4–6% modifying traditional road conditions. Only, mountainous countries like Switzerland and Austria developed inland communication systems, employing the latest technology (Gothard Railway, 1882 – links to France and Austria in 1860), unlike other countries that preferred to maintain the main transport networks in mountainous areas just as they were before.

The motor revolution in the 20h century seems to modify the conditions in the mountainous regions. Engineering work such as long tunnels, viaducts and bridges appears to have overcome obstacles by gaining access to the mountainous regions. Despite this, the preference for mountainous routes remains the same more or less as during Roman times, even though with improvements in cost, time and safety. Even with engineering works, no alternative route became more popular due to expensive tolls, lack of infrastructures or economic pressures (Molitor et al., 2001).

2. Conditions of Roman land transport in mountainous regions

Normally when travelling, people avoid crossing mountainous regions whenever possible, but some routes across mountains were sometimes necessary for military, political or even commercial reasons. Therefore, Romans built roads to overcome all the potential inconveniences of mountains. Most problems arose with the steepness that transport means had to tackle to reach the summits. Humans can cope with any kind of gradient, but loaded wagons pulled by animals, could seldom deal with gradients larger than 5% (Lawton, 2004). Therefore, pack animals were the only means of transport in the highest part of the mountains, so it was essential to change the means of transport to overcome those steep mountains roads.

Gradients were not the only difficulty related to transport in mountainous regions, as other conditions also discouraged the use of those roads, or even developing suitable road infrastructures:

2.1. Problems of gradient

As mentioned before, gradient was the obvious problem for land transport. Lawton (2004) suggests that wheeled transport could theoretically deal with gradients larger than 5%. Moreno (2006, 48) increased this percentage to 6–8% in accordance to empirical values obtained from some roads in Hispania. In fact, the road crossing the Alps evidences wheel tracks in parts with gradients between 6,7–10% (e.g. Bard, Pierre Taille, Montquert) (MolloMezzena, 1992).

Experts base reconstruction of ancient prehistoric routes, on low cost path (LCP) analysis that take into account the land surface and gradient. The Tobler hiking function is applied to those studies regarding individual walkers (affected by age, gender and fitness), reaching a 25% of metabolic consumption by increasing and reducing gradients (Herzog, 2013).

$V(s)=6e - 3.5\ |s+0.05|$

Calculations on wheeled-vehicles differ from those on walkers due to differences that makes transport by animal-drawn vehicles of more than 10% gradient very difficult.

Verhagen and Jeneson (2012) applied a cost function for wheeled vehicles with a critical slope over 15% in their Least-Cost Network in GIS to calculate the Roman road in the mountainous region of Limburg (Nederland). Likewise, Herzog (2013) established critical slopes between 8 and 10% in the Rhineland roads for vehicles drawn by oxen, based on the inductive evidence on the provincial roads gathered by Grewe (2004, 30), which do not exceed more than 8% gradient. Exceptional gradients of 16–20% are also mentioned but with no archaeological evidences.

As a result, Romans built roads avoiding larger gradients when possible, but it was sometimes difficult to cover the whole itinerary without steep gradients. At this point a change in means of transport from a wheeled vehicle to a pack animal was necessary. For steep slopes, ruts could be cut into the rock creating "track roads" specially suitable for both animals and humans (Bulle, 1948; Grabherr, 2006, 109; Schneider, 2007) or even stairs (Schuler, 1998, 135; Kolb, 2012, 56;). Pack animals are capable of climbing up gradients around 43% on stable surfaces, so they are the most suitable means of transport on steep slopes.

If the change in means of transport was necessary before getting to the "track roads", there would have been a mansio or mutatio to provide the pack animals and switch the wagons pulled by mules or oxen. Most Alpine and Pyrenees mountain passes required this change in transport to overcome the final steep slopes.

2.2. Wagons, harnessing and brakes

Most heavy loads transported by wagons pulled by oxen or horses, with a limited weight to of 492 kg in the case of horses and 750 kg when drawn by oxen according to the Theodosian Code (438 CE) (angaria- C.Th.8.5–6). An ox-drawn wagon was pulled by 3, 4 or 8 oxen on flat surfaces and was considered slow mail and called cursus public sclabularius. Those load restrictions were only applied only on level surfaces, as pulling weight would require a bigger effort on any steep slope.

Roman wagons were 2 or 4 wheeled vehicles, with 8 or 10 spoke wheels rimmed with iron, pulled by oxen or horses (Raepsaet, 1982, 236) (see Fig. 1). The archaeological site of Neupotz produced 8 iron axle fittings that reinforced the wagon's structure so that it could carry a weight of 3 t. Some of the iconographic evidence suggests that Romans strengthened these vehicles by with a block acting as a brake on the wheel rim or by a footboard, which also had a braking function (Weller, 1999). Molin (1984) deeply studied the Langres style wagon and has reconstructed the brake system as one operating with a combination of brake shoes and a chain.

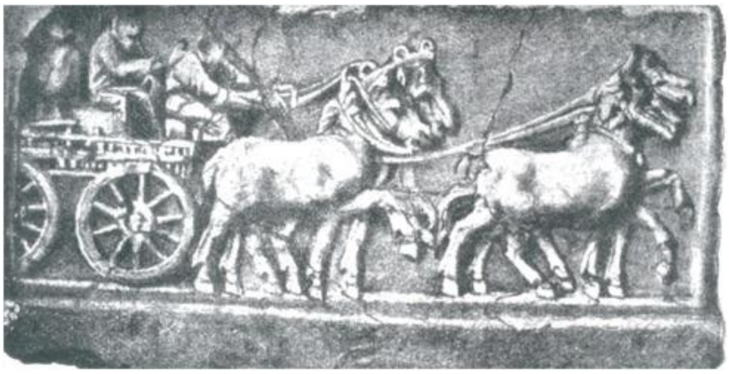

Figure 1. Rheda from Langre

As far as harnessing, recent research and experiments have confirmed that the collar harness for shoulder traction had already been introduced in Roman times (Brownrigg and Crouwel, 2017) and not in during the medieval period as most experts defend. Roman funerary reliefs from Central Europe showing wagons do not clearly show how the harnessing system worked, but the recent harness discoveries from Le Rondet (Switzerland) have provided information about the resence of a yoke (made out of metal or wood) with an iron U-shaped piece connected to wooden planks (Brownrigg and Crouwel, 2017, 204). There have been successful reconstructions of this neck harness tested without strangling the draft animals (see Fig. 2).

Figure 2. Experiments of collar harnessing (Brownrigg and Crouwel, 2017, Fig. 21b)

Pack animals carried between 90 and 120 Kg (Leighton, 1972; Landels, 1978; Carreras and De Soto, 2010, 89) at a speed of 5–6.5 Km/h. However, loads would have been lighter in mountainous conditions; also, speeds were probably reduced by 20% with changes in altitude above 300 m. The Pisidia's Edict issued in a mountainous region of Anatolia (Mitchell, 1976) established the equivalence of 1wagon as with 3 mules or 6 donkeys, which reveals the importance of these pack animals in highland environments.

2.3. Weather conditions and transport infrastructures

Through winter the extreme weather conditions affected transport in the mountainous regions due to snow and ice on the main routes. These conditions limited land transport during winter periods except for military reasons. These harsh conditions required specific transport infrastructures to avoid muddy roads as well as to increase the frequency of mansios to give shelter to travellers.

A few natural features such as rivers or mountains were overcome by building bridges and tunnels (only small ones), that required a continuous maintenance and sometimes a control point to pay tolls. Strabo (V.4.7) and Seneca (Letters 57, 1–2) already mention tunnels ordered to be dug by Augustus in the 1st BCE, but archaeologically the Grotta di Cocceio(1 Km long near Naples) is the oldest tunnel documented in 38–36 BCE. However, an exceptional example in the Apennines is the Furlo Pass (only 37 m long but still in use) dated from the Vespasian period (69–79 CE), and was a construction to be remembered in later generations (Aur.Vict. Caesar 9) (Laurence, 1999). Also, there are other Roman tunnels in mountainous regions such as in the Balkans.

Furthermore, mountainous regions normally became borders between different Roman provinces, so there were towns or official headquarters to control the frontiers and farm taxes (portoria – quadraguessima or quiquagessima) at stationes. Most of those infrastructures were also in use during medieval times, so mansiones and stationes became monasteries or hospitals on the pilgrimage routes providing accommodation and tax-collection points (Alps: Cavallaro, 1999; Pyrenees: Riera, 2002). In the case of the Pyrenees, in addition to the coincidence of roads from Roman to Medieval times, some hospitals coincide with mountain ports were roman remains have been found (Hospital de Bensaque) and roman inscriptions in monasteries at crossing points such as bridges where tolls were (i.e.Santa Maria d'Alaó; Santa Maria d'Obarra).

2.4. Soils, terrain, water and coverage

Historical and archaeological evidence of Roman roads vary depending on the province and territory, but in general, there is still a lot to learn. There have been some attempts to employ network construction techniques, based on different thematic maps (sites, soils, weather) in order to generate a potential network of local roads, tracks or pathways. Many variables may affect the construction of a particular network infrastructure on a local or regional scale.

Firstly, the pattern of population distribution in the region and closeness of different settlements are the key proxies to establish potential contact by means of a transport network. Secondly, the localization of the network depends on the landscape conditions such as type of soils, water, vegetal coverage and gradient. Lastly, once the potential network is defined, different means of transport (i.e. walkers, oxen drawn-vehicles, pack animals) may obtain different results from the movement on such routes.

The project of “Finding the limits of the Limes” (Groenhuijzen and Verhagen, 2015, Groenhuijzen and Verhagen, 2017) applies these principles to reconstruct local transport networks in the Roman Netherlands considering the documented Roman sites, palaeogeographical conditions at a 20 min distance. It uses efficiency networks models to generate a network transport proposal calculating cost values by the Pandolf et al. formula (1977). Due to the flat conditions of the study area, they established an identical isotropic cost in both directions (Groenhuijzen and Verhagen, 2017) in other words they did not need to take the gradient into account the gradient.

3. Modelling Roman land transport networks

The introduction of GIS into archaeology in the late 90s implied a new methodological approach to the transport analysis in archaeology (Wheatley and Gillings, 2002). Most applications were based on human movement on least-cost paths on raster maps. Initially those least-cost paths (LCP) took into account only the slope gradient, so a previous Digital Elevation Model (DEM) was required to calculate friction movement and direction (Rogers, 2014, 37). It should be kept in mind that the accuracy of the analysis of the LCP is linked to the degree of accuracy of the DEM.

Since the first decade of 2000, free DEM data can be obtained with an acceptable level of detail for the study of transport networks. The Shuttle Radar Topography Mission (SRTM) project carried out by the NASA in 2015 has allowed us to have 30 m DEM precision worldwide. In the case of mountain passes, it would be advisable to have DEMs with about a 5 m accuracy. This entails an exponential increase of data to be processed[1] to make the LCP and most of these high accuracy models are not freely accessible. In addition, when dealing with borders in mountainous areas, the problem could be that the data of one of the countries are is not free, and therefore a complete model of the mountainous area cannot be accomplished. This is the case with the work of Muñoz (2017), in which the model of 30 m of the STRM had to be used, because only the free data with a 5 m accuracy was available for the Catalan side of the Pyrenees and the French part was also necessary so as to complete the LCP to Elna.

With LCP applied to a DEM, it is possible to envisage which mountain passes were most-likely to have been used as they presented less difficulty (Llobera et al., 2011) and also the time involved if a hiking formula is applied (Tobler, 1993). In recent years, different authors published proposals for more complex calculations (see Herzog, 2014). The exclusion of inaccessible areas (due to flooding) (Fiz and Orengo, 2008), or the compulsory passage through archaeologically detected points, have been combined with other more social or cultural aspects, such as the existence of sacred or taboo areas (Llobera, 2000; Grau, 2011).

The case of Roman and medieval transport is slightly different as it involves a stable road infrastructure and a variety of means of transport. Again, our research employed a DEM model to establish the suitability of particular means of transport (see Fig. 3 for the Segre route). Gradients larger than 5% were impossible for Roman wagons, so this factor limited their use (Lawton, 2004). Regarding pack animals, there are no such limitations except for at critical points. Pack animals face difficulties crossing rivers or climbing steep hills (Fig. 4). These

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[1] The values of a DEM are contained in a raster-type file in which each pixel represents a value of precision x. Then, in a DEM of the Pyrenees with a precision of 30 m, we will have n number of pixels, that will exponentially multiply with a DEM of 5 m, thus having a raster file of larger dimensions to process with the LCP.

conflictive points required a particular type of transport infrastructure that should have left some sort of archaeological trace or have continued to be in use up to modern times.

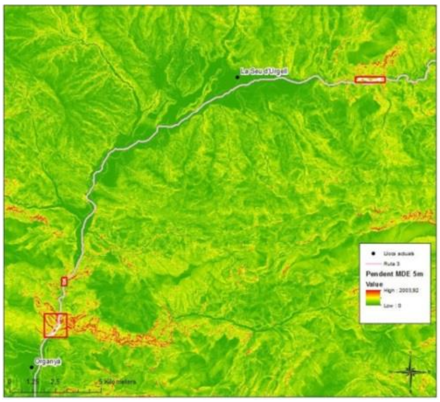


Figure 3. Gradients from DEM model limited for pack animals in river Segre route (Pyrenees) (Muñoz, 2017, 67: Fig. 34)

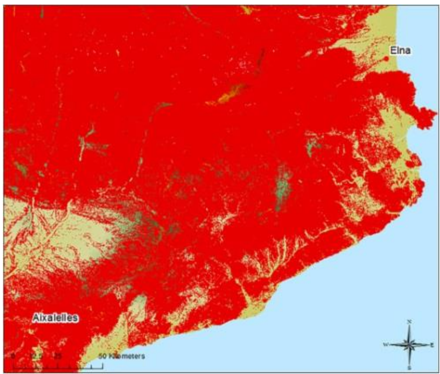
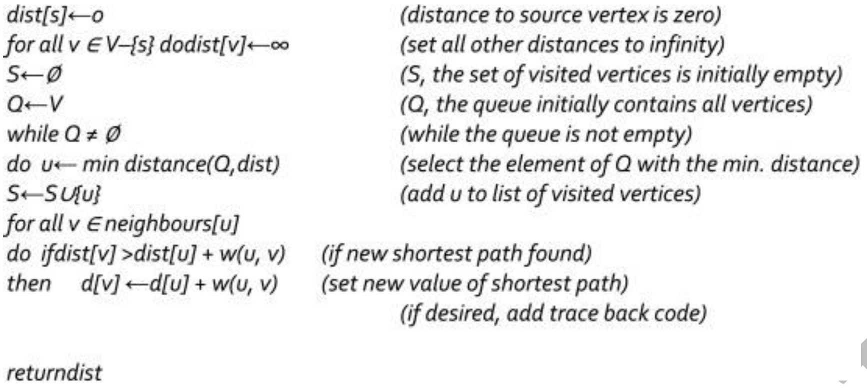


Figure 4. . Wagon limitation areas from a 5% gradient restriction (in red) in NE Iberian Peninsula. (Muñoz, 2017, 67: Fig. 9)

Another different technical application of GIS developed for network analysis modules, is especially adequate for sophisticated transport networks, combining different means of transport, and it can also obtain cost and time consumption. The main base for these calculations is the knowledge of a well digitilized transport network, which should include the land routes and also the navigable rivers and sea connections. The combination of the established transport network with Ancient travel speeds and costs, allows the creation of transportation models and distribution areas for the goods. One of the first attempts to reconstruct the functioning of the Roman transport networks, was a case study of the Roman Britain (Carreras, 2000). Few years later, a similar but more complex approach, was applied to analyse the Roman infrastructures in Britain, the Iberian Peninsula and Italy, and also to evaluate the diachronic evolution of transport in the Iberian Peninsula until the 19th century (Carreras and De Soto, 2010) (see Fig. 4). De Soto (2010) has been developing new studies using very detailed networks, trying to obtain more close-to-reality results (De Soto, 2010; De Soto, 2018). There are also other projects that have tried to model the transport system of the whole Roman Empire (Scheidel, 2014) but so as to accomplish such an ambitious goal, it was necessary to reduce the detail of land roads and only use the major Roman routes.

Nowadays it is possible to calculate the transportation cost of Roman goods using the shortest paths functions available in some GIS software in addition to some improvements in the cost values and network data. The shortest path based on the Dijkstra's Algorithm (1959), published as:



```
dist[s]←o                              (distance to source vertex is zero)
for all v ∈V–{s} dodist[v]←∞          (set all other distances to infinity)
S←Ø                                    (S, the set of visited vertices is initially empty)
Q←V                                    (Q, the queue initially contains all vertices)
while Q ≠ Ø                            (while the queue is not empty)
do  u← min distance(Q,dist)            (select the element of Q with the min. distance)
S←S∪{u}                                (add u to list of visited vertices)
for all v ∈neighbours[u]
do  ifdist[v] >dist[u] + w(u, v)   (if new shortest path found)
then     d[v] ←d[u] + w(u, v)      (set new value of shortest path)
                                       (if desired, add trace back code)

returndist
```

The first algorithm finds the best route between two nodes, but the most popular algorithm has been the one that calculates the route between one node to and the rest of the nodes in the network. It works by calculating the distance between nodes, updating the distance costs when it finds a smaller one. The success of this algorithm is to obtain reliable results about transport costs based on the value of each. These values should be based in on a deeply and concise historical transport data to obtain the best possible route calculations.

In our project, the digitisation of the Roman transport network allowed us to obtain a reliable information on the distance of each edge information about each edge of the transport network. In order to create a more complex model, we included, not only the terrestrial networks but also the Roman navigable rivers and the sea connections. Previous studies covered a detailed explanation of the Roman transport values used in these analyses (De Soto, 2010; Carreras and De Soto, 2013). This research obtained the results by calculating the weight of each edge based on its length and the cost values (both in time and expenses) to each distance unit depending on the means of transport (sea, upstream-downstream river and land), it represents (Table 1). Several ancient sources were taken into consideration in the choice of these key values, archaeological remains and historical and ethnographical data. Despite the fact that there are some differences between transport projects, there is a great general coincidence in the ratios between sea, river and land transport.

Mean of Transp.	Speed	Capacity	Cost (Kg Ton/Km)	Ratio
Sea	4,25 Km/h	92 T	0,097 Kg Ton/Km	1
River (Downriver)	2,5 Km/h	5,5 Ton	0,33 Kg Ton/Km	3,6
River (Upriver)	0,6 Km/h	5,5 Ton	0,66 Kg Ton/Km	6,8
Cart	1,6 Km/h	386 Kg	4,92 Kg Ton/Km	50,7
Pack Animal	4,5 Km/h	90 Kg	4,21 Kg Ton/Km	43,4

Taula 1. Roman transport costs (Carreras and De Soto, 2013)

Even though there are some differences between transports values within the projects focused on this topic, there is a great general coincidence in the ratios between sea, river and land transport. Past studies obtained big differences between the cost results of water transport and land transport (Table 2): Duncan-Jones (1974) 1 sea; 4,9 river; 28–56 land, Künow (1980) 1 sea; 5,9 river; 62,5 land or Deman (1987) 1 sea; 5,8 river; 39 land. More recent studies also coincide in obtaining similar relationship between every mean of transport: Scheidel (2014) 1 sea;5 (downriver)/10 (upriver); 52land or Carreras and De Soto, 2010, Carreras and De Soto, 2013: 1 sea; 3,6 (downriver)/6,8 (upriver); 50,7 land.

Mean of Transp.	Duncan-Jones	Künow	Deman	Scheidel	Carreras/deSoto
Sea	1	1	1	1	1
River (Downriver)	4,9	5,9	5,8	5	3,6
River (Upriver)	4,9	5,9	5,8	10	6,8
Cart	56	62,5	39	52	50,7
Pack Animal	28	62,5	39	52	43,4

Taula 2. Roman transport costs ratios

Using the costs obtained of the Roman transport (Table 1) it was possible to analyse how the network worked by calculating the expense in time and travel costs to transport certain products from one place to another. In the case of Britain, as in most of the Roman networks, there are big differences between the results from calculating the shortest path (distance), the cheapest (cost) and quickest (time) routes (See Fig. 5). The results of shortest paths calculations in terms of distances always offers the straightest route between two points whilst the cheapest route tries to find the best result using the edges with smaller transportation costs (usually sea and river connections). Finally, the search of the quickest route combines the straightest route along the edges with the quickest vehicles. In the case of the Fig. 5 the shortest and quickest route coincides but in some cases they could be slightly different.

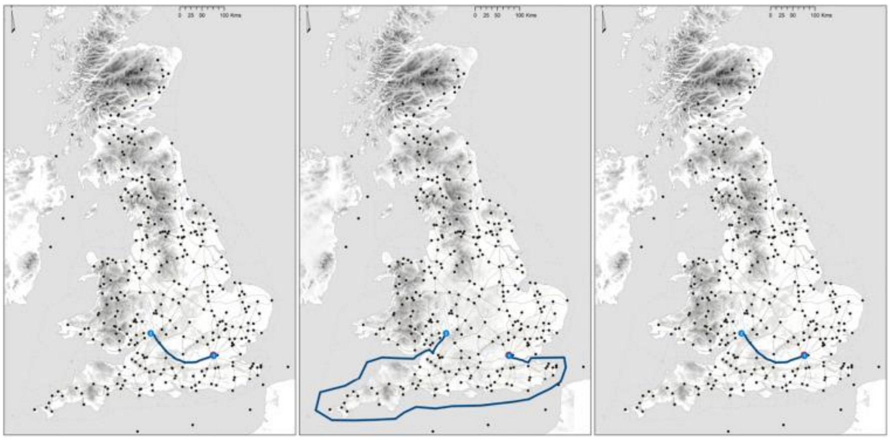


Figure 5. Comparison between shortest path (left), cheapest route (centre) and quickest route (right) of Roman Britain between Londinium (London) and Glevum (Gloucester).

In our projects, following the same procedures explained below, we performed calculations from one node to the rest of the nodes in the network. Then we interpolated quantified results from the values obtained for each node to generate heatmaps of transport costs and time expenses to travel across big territories (see Fig. 6, Fig. 10, Fig. 14).

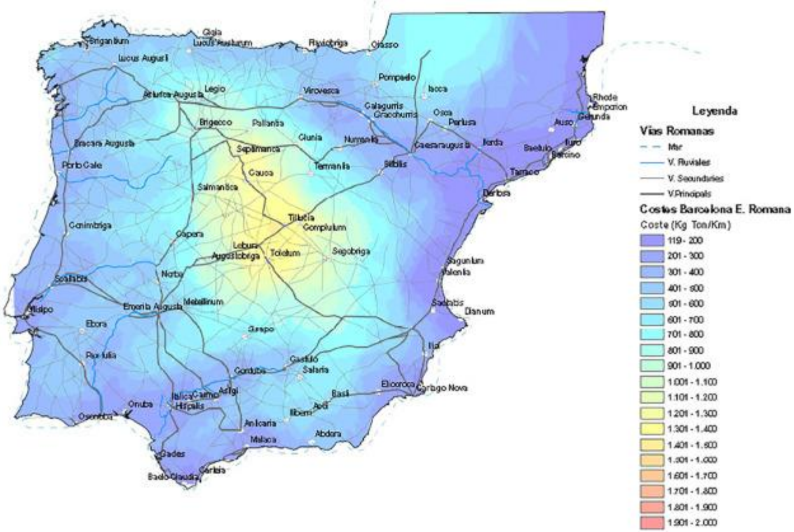


Figure 6. Transport costs (Kg Ton/Km) from Barcino (Barcelona) to the rest of the Iberian Peninsula (Carreras and De Soto, 2010, 206) (blue colours with the lowest transport costs).

Past analysis of the transport networks showed the shortcomings of plain areas to design, the Roman transport networks (Carreras and De Soto, 2010, Carreras and De Soto, 2013). The case of the Iberian Peninsula for example, shows the well-connected and easier goods transport along big plain areas, such as on along the Mediterranean coast and the river valleys. Despite the fact that mountainous regions, appear to have been major obstacle for the land transport infrastructure until recent times, the combination of LCP and network analysis applications allow us to understand the use of particular passes, the means of transport used and the economic outcomes.

4. The Italian Alps: the great barrier

Most of our knowledge on land transport in mountainous zones in the Roman period comes from the evidence from the Alps. This mountain range separates the Italian Peninsula from Central Europe, and even today, it is a perfect barrier between these two regions. One of Hannibal's first achievements was to cross the Alps with his Carthaginian army and elephants in the winter of 218 BCE (Polybius 3.50–55; LiviusXXI.32.37.6) probably through the col. de Mongenèvre[2] during the crossing of which he had to face the hostile Allobroges.

Polybius (III.50) describes the difficulties facing the Carthaginians faced to transport their baggage through the pass in the Alps quite well: “But later, as they watched the long train of pack animals and horsemen slowly and painfully making their way up the narrow track, they were tempted to harass the advance”. During the Republic, there were routes and tracks crossing the Alps that represented great challenges for any trader or army. With the permission of the local tribes that really controlled the few good passes, they covered the area on foot with pack animals (horses and mules).

Rome fought against all those tribes controlling the Alps routes until Augustus finally conquered the Great St. Bernard pass from the Salassi, who were totally defeated and reduced to slavery (DioLIII.25; Strabo IV.6.7). The importance of this campaign was that it secured made the crossing from Italy to Upper Germania, a newly conquered province, secure. Despite having achieved a military control of these key mountainous land routes, Rome required needed the region to be peaceful in order to foster trade and to make exchanges them. That is why; the victorious general Murena also founded in 25 BCE the colony of Augusta Praetoria Salassorum (the modern city of Aosta) (MolloMezzena, 1987) (see Fig. 6) (Fig. 7).

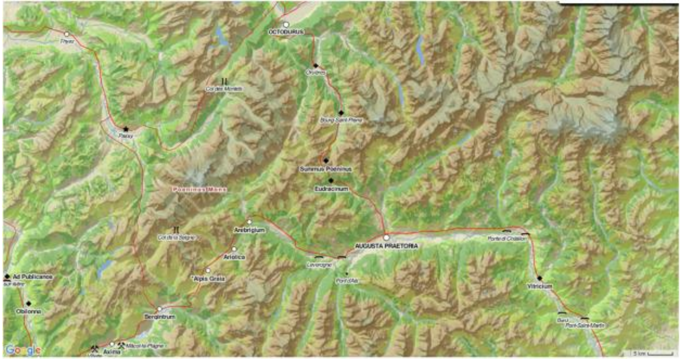


Figure 7. Location of Augusta Praetoria and its main routes (Pelagios project).

It seems that the location of Augusta Praetoria on the route from western Gaul to Iulia AugustaTaurinorum (Turin) made it the best candidate to set up a statio for collecting tolls (portoria between the province of Lugdunensis and Cisalpina)[3]. However, such these commercial incomes were not the main reason for controlling this region and founding the colonia, instead it could have been the wish to create a safe military corridor (via militaris).

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[2] Livy XXI.32.37.6 refers to the river Druentia, which is probably the present Drôme.

[3] There is an inscription of the imperial slave Bassus, who was a circitor, in other words a tax-collector (Quadragessima Galliorum – 2.5%)

Augustus was responsible for the conquest of this territory, even though Claudius was the emperor who really developed all the road infrastructures that eased the crossing over Grand Bernard pass (2.469 m) and the Little Bernard pass (2.188 m) (MolloMezzena, 1992).

The route went from Octodorum (Mattingly) to St. Remy, which was 27 Km away from Augusta Praetoria, before ascending to the Great Bernard Pass and later descending towards Augusta Praetoria. At the top of the pass, there was a temple dedicated to Iuppiter Poenius, and a possible mansio that gave shelter to merchants and pilgrims (see Fig. 8). Likewise, the Little Bernard Pass provided another mansio for the travellers.

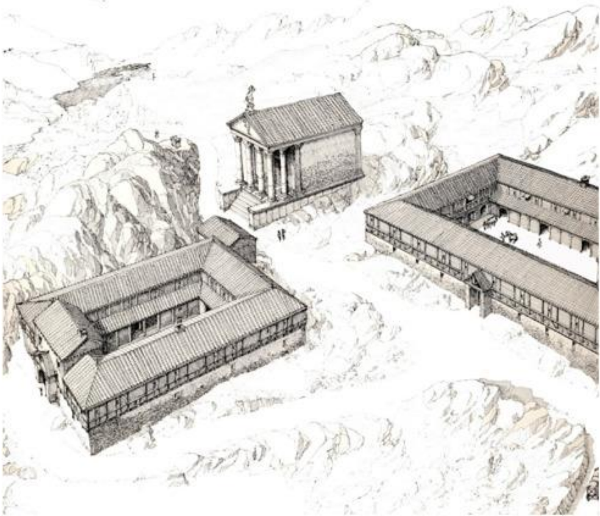


Figure 8. Top of the Great Bernard Pass with the temple of Iuppiter Poenius (MolloMezzena, 1992).

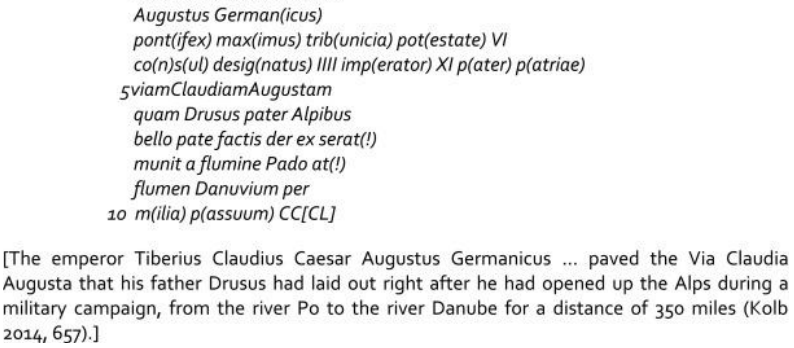
The road reformed by Claudius required sophisticated engineering to overcome the steep gradients, landslides and water movements. There are parts at Bard with gradients larger than 6–8%, at Montquert of 10% and Pierre Taille of 7%, which were almost impossible for heavy wagons (MolloMezzena, 1992, 62), so only light carts and pack animals could cover this part of the route. Roads were cut into the rocks and had drains to remove water from the road surface (see Fig. 9). Such a great effort in building this transport infrastructure cannot be explained in economic terms. Traders could only carry high value goods across these Alps routes if they expected any kind of profits after subtracting the production, transport and taxes (Carreras, 2000). Therefore, traders supplied raw material such as food to other provinces by boat, because the Italian Peninsula became an island in terms of transport costs.

Figure 9. Roman road at Donnas.

GIS modelling costs and time consumption for different land routes from Italy to other provinces, confirms the high cost and time consumption there was in covering the Alpines routes, so only the coastal route via Albintimillium (Ventimiglia) would have been economically viable (Carreras and De Soto, 2013). Fig. 10 shows an attempt to exemplify transport cost from the city of Rome to other locations in the Italian Peninsula following the methodologies and using the values explained in Section 2. Apart from the evident difficulties of crossing the mountain range of the Apennines, there are obstructions to reach the Apulia in the south and, of course, the Alps formed a major barrier.

Figure 10. Transport cost from Rome to the rest of the Italian Peninsula (Carreras and De Soto, 2013) (green colour with the lowest cost values).

A few mountainous routes crossing the Alps were available to move armies, send couriers and transport some products, as were clearly exposed by some historical sources like a milestone erected by Claudius in 46 CE describing the history of the Via Claudia Augusta (CIL XVII, 4,1):


Ti(berius) Claudius Caesar
Augustus German(icus)
pont(ifex) max(imus) trib(unicia) pot(estate) VI
co(n)s(ul) desig(natus) IIII imp(erator) XI p(ater) p(atriae)
viamClaudiamAugustam
quam Drusus pater Alpibus
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flumen Danuvium per
m(ilia) p(assuum) CC[CL]

[The emperor Tiberius Claudius Caesar Augustus Germanicus ... paved the Via Claudia Augusta that his father Drusus had laid out right after he had opened up the Alps during a military campaign, from the river Po to the river Danube for a distance of 350 miles (Kolb 2014, 657).]

Some routes existed before the Romans as it has been attested from the trade and commerce of amber (Route of Amber) connecting the Adriatic Sea and the Baltic Sea and the probable route of the Argonauts to the Black Sea that denotes the existence of passes through these chains (Mlekuz, 2014 16). However, the Romans considered that the passes of the Alps were almost difficult as Diodorus Siculus (IV.19.3) said:

"Heracles then made his way from Celtica to Italy, and as he traversed the mountain pass through the Alps he made a highway out of the route, which was rough and almost impassable, with the result that it can now be crossed by armies and baggage-trains."

These epigraphic and written testimonies provide the geographical importance of the Alps as far as the Romans are concerned as well as the importance to be able to cross them for both, military and commercial reasons. The Alps are located as a physical barrier between Italy and significant territories of northern Europe, which is the reason why they need these land routes to be built with such care. In logistic terms they were vital and also so the information and political communications for the Roman Empire could flow.

A detailed study of the main Pennine Alps passes on the basis to land cover and slope (see Fig. 11) (Rogers, 2014, 64), confirm the fact that Roman roads were located following the line of most accessible alpine tracks and provided a suitable time expenditure.

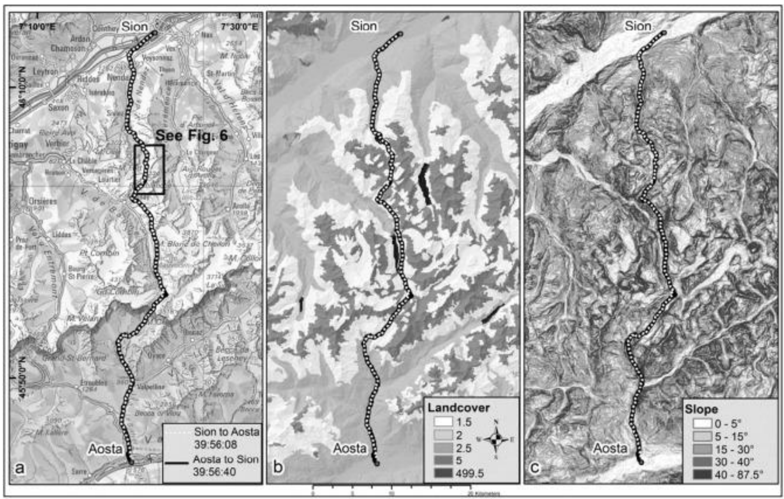


Figure 11. LCP from Aosta to Sion on the basis to land cover and slope (Rogers, 2014, 64, Fig. 5).

5. The Pyrenees: the last wall towards the south

In the recent years, we have been involved in the excavation of Iulia Libica (Llívia), a Roman town in the middle of the NE Pyrenees in the province of Hispania Tarraconensis. Therefore, our research has focused on understanding the reasons behind this municipium foundation and its role in land transport in this area of the NE Pyrenees (Guardia et al., 2017). From the early Roman Republican period, there were three main routes crossing in the NE Pyrenees (see Fig. 12), even though the easiest one was the via Heraklea (later via Augusta), parallel to the Mediterranean coast with nearly no slopes. (See Fig. 13.)

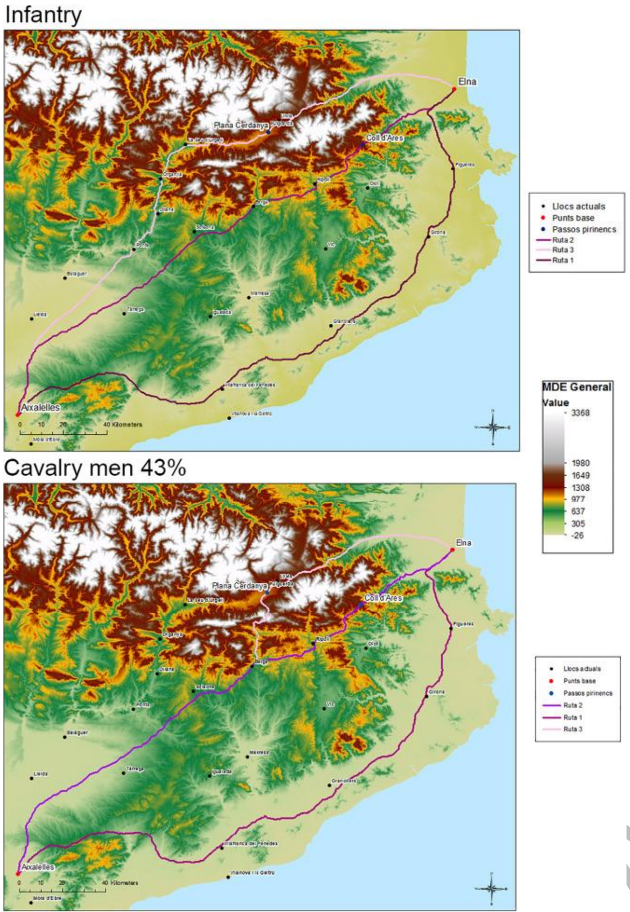
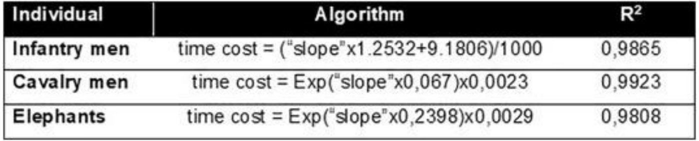


Figure 12. Three main routes crossing the Pyrenees in NE Spain for infantrymen And cavalrymen (Muñoz, 2017, 31: Fig. 8).



Individual	Algorithm	R²
Infantry men	time cost = ("slope"x1.2532+9.1806)/1000	0,9865
Cavalry men	time cost = Exp("slope"x0,067)x0,0023	0,9923
Elephants	time cost = Exp("slope"x0,2398)x0,0029	0,9808

Figure 13. Individual algorithms for LCP' s infantrymen, cavalrymen and elephants. (Muñoz, 2017, 36).

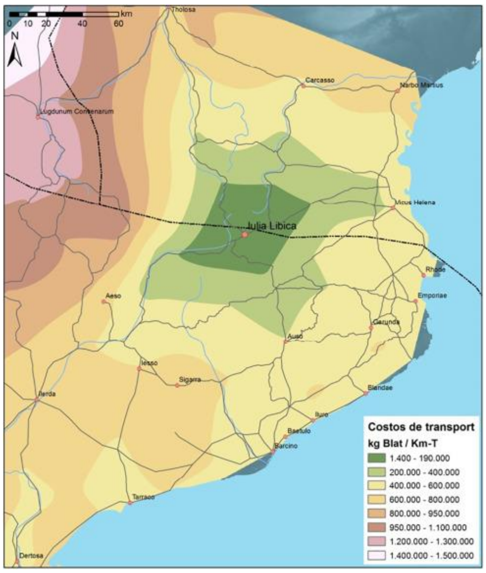


Figure 14. Transport costs from Iulia Libica (Kg wheat Ton/Km2) (Guardia et al., 2017, 168: Fig. 21) (green colour with the lowest costs).

Fig. 14

In the summer of 218 BCE, Hannibal crossed the Pyrenees with 80.000 men, 11.000 cavalrymen and 37 elephants (Polybius XXXV.2; Livius XXV.2–3; Appian, Hann. 4) from possible camps near Aixalelles to Illiberis (Elna), avoiding the coastal route controlled by the Romans near Emporion. Muñoz (2017) tried to evaluate which of the two possible routes (route 2 or 3) were used by applying LCP (Least Cost Path)with GIS. The LCP was applied on a 30 m DEM for all the routes (from Aixalelles to Elna) and a 5 m DEM for the problematic situation of what would probably be route 3 of infantry men that goes near the river Segre. Both DEMs were obtained as free data from the SRTM NASA project and the Institut Cartogràfici Geològic de Catalunya (ICGC), respectively. In addition to this, it was necessary to assign an algorithm to each sort of being that formed part of Hannibal's army. To achieve that, a correlation, in time (minutes), between the individual speed and the effect of the slope gradient on it, was needed (see Fig. 12). The limitations in gradient that were applied were 43% gradient for cavalry men, 13% gradient for elephants and 5% for wagons (Lawton, 2004).

The consequent slope map from the SRTM's DEM showed that Hannibal's troops could not have used wagons, as some parts of route 2 by Coll d'Ares (Prats de Molló) and route 3 by Coll de la Perxa (Alta Cerdanya) documents gradients of more than 6–10%. Infantrymen did not have any problems to go along these routes, but neither elephants nor cavalrymen could have faced some critical points in the Segre route at the Tresponts (Organyà) and a narrow gorge 5 km long from Seu d'Urgell (see Fig. 3, Fig. 12). Because of this slope limitation, the proposed LCP route 3 for infantrymen was not the same for cavalrymen (see Fig. 12) who avoided the Segre path.

Therefore, the author concludes that the most feasible route was via Coll d'Ares or even the possibility that the army split into two, each taking one of the two routes in less than 11 days.

The munipium of Iulia Libica founded in the time of Augustus, lies in the middle of the route 2. The two critical points of this route were solved by building three bridges in the narrow gorge of Organyà (Trespont), which were also rebuilt by Bishop Ermegol of Urgell in the 11th century (Padró, 1976). The whole route continued to be recorded throughout the medieval period and was called "strata Ceretana", and expanded from Perpignan (ancient Ruscino) following the Tet valley to Villafranche du Conflent and subsequently to col. du Perche (1579 m), Llívia (ancient Iulia Libica), Puigcerdà, Seu d'Urgell, Balaguer and Lleida (Campillo and Mercadal, 1997).

Modelling travel time costs and expenses by applying network analyses with GIS software, using the methodologies explained in Section 2, shows that routes 2 and 3 could have offered little competition to the coastal route 1, that had become the most frequently used during the Roman period. So, why was Iulia Libica founded halfway along the route? As in the case of Augusta Praetoria, it seems that military and administrative reasons lay behind its foundation. The municipium of Iulia Libica was the last urban centre in the province of Hispania and probably acted as a statio, farming taxes for crossing provinces (portoria: quiquagessima Hispaniorum – 2%) as in the case of in the Roman town of Lugdunum Convenarum (Saint Bertrand de Comminges) in the Central French Pyrenees (Esmond Cleary, 2008, 87). Besides, the Segre itinerary had been an important military route since Republican times when Pompey or Caesar reached to the mid Ebro valley travelling, along this line.

Simulating transport costs and time from Iulia Libica, it is evident that the municipium depended on local of Gaulish resources rather than Hispanic ones, since as communications with the rest of the province were complicated. The route towards the Tet valley and Ruscino (Perpignan) only involved negotiating the Col de la Perche (1579 m) (Guardia et al., 2017). Recent studies on importation of ceramic and marble imports at Iulia Libica, conclude that most of them came from the Gaulish side, both in the case of fine ware (Southern-Gaulish sigillata), coarse wares (white coat ware, grey ware) as well as local marbles from the Saint Béat and Vilafranche region (Guardia et al., 2017).

Therefore, Iulia Libica may have operated as a control point on this route across the Pyrenees without any commercial interest, but it was an important strategic pass in terms of military logistics. Likewise, other Roman cities in the Pyrenees founded by Augustus in the last quarter of the 1st century BCE seem to have fulfilled a similar role as in the case of Iturissa (Burguete) controlling the Roncesvalles route or Iacca (Jaca) in the pass of Coll de Somport.

6. Discussion: the last conquest, Roman roads in the high mountains

Augustus conquered most mountainous areas in the Western Roman Empire from the Asturo-Cantabrian range to the Alps and the Pyrenees in the last decades of the 1st century BCE. They were the last no submitted territories within the Roman frontier controlled by indigenous highland tribes, but without rich economic resources.

The reason behind these conquests and their later urbanisation by Augustus reflects an overall policy of controlling land transport routes for communication and strategic reasons (Kolb, 2012–1). The development of the cursus publicus (public transport network) with its associated infrastructures of built roads, mansiones, mutationes and stations, required isolated mountainous regions outside the Imperial control and were to be conquered. In spite of this military control and urbanisation, mountainous routes were still the hardest and most difficult parts of the road network.

However, the transport network in the mountainous ranges worked quite well during the High Empire, but it seemed to lose strength from the end of the second and third century onwards. Some urban centres in these regions, for instance in the Pyrenees, reduced their size and documented less foreign material and others were abandoned in the late period. The discussion lays on why social and economic contacts were limited when the road infrastructure still remained in good state.

Simulating routes with GIS allows us to assess their individual performance, time and transport costs and “critical points” on every individual route. High mountains became major barriers for land transport and they are still today, despite the technological developments. Only determined Roman policies made it possible to create these first land corridors in the Alps and Pyrenees, which became networks for the civilisation the wild mountainous regions, and which continued likewise in medieval times.

Modelling transport in GIS provides suitable data suitable in terms of cost and time to understand specific quantities of importations documented in mountainous towns such as Augusta Praetoria (Aosta) or Iulia Libica (Llivia). It allows us to give an explanation of why some importations do not appear on one side of the mountainous range such as Dressel 20 amphorae in Northern Italy, southwards the Alps a big amount appear North of the Alps.

At the present, such Roman transport models tested the distributions of archaeological material along these routes and key points on the road network infrastructure. In the NE Pyrenees, performance results are compared to the quantity of pottery, coins and marble that appears in the Cerdanya region and the city of Iulia Libica (Guardia et al., 2017), but can help to understand transhumance routes and political events. Comparing the quantity of material from other towns in the Pyrenees on both sides, we can assess the performance of the different routes and their evolution over time which appears to be one of the most remarkable phenomena recorded so far.

7. Conclusions

The present paper analyses how the mountainous ranges such as the Alps and the Pyrenees became key obstacles in the development of the Roman roads. However, the Romans put a lot effort and resources into the infrastructures in the mountainous regions, because they became strategic for military, administrative and economic reasons. However, when this strategic role decreased from the third century onwards, the economic and social functions were not enough to maintain these mountainous routes, and therefore lost importance.

Modelling transport networks in GIS has becomes an alternative way to study these land routes from different points of view, as also to study their efficiency in terms of cost and time.

The values generated in these synthetic models can be used to interpret material recovered in with the archaeological record, along these mountainous land routes.

At present, we are studying all the physical evidence (pottery, marbles, and coins) in detail, from different towns along the main routes crossing the NE on both sides of the Pyrenees. Thus, we identify the origin of these materials and their movement from the production areas to the consumption areas with the help of values obtained in our GIS transport models. Such detailed GIS models reveal critical points in the networks (rivers, gorges, mountain passes), that involve changes in means of transport, speeds and probably costs.

Finally, future research will involve a diachronic approach in order to understand how these routes evolved up to present with no major changes despite evolution in means of transport, engineering works, speeds and costs.

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