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11 Reconstructing past movement patterns on the basis of known old roads. A case study on pre-industrial roads in a hilly area in Germany

11.1 Introduction

Many ancient roads serve as evidence of continuous movement over extended periods of time. Their analysis provides insights not typically found in historical travel accounts. However, identifying the historical network of major travel routes within a specific study area – based on both historical and archaeological evidence – is a complex task. This is precisely what the geographer Herbert Nicke has accomplished in his publications on ancient trade routes in a mostly hilly region situated east of Cologne, Germany (Figure 11.1).[1] Nicke's work utilises historical maps, travel records, and other historical sources, in addition to landscape observations. Regarding Nicke's descriptions of the medieval and early modern routes as faultless, the objectives of the present analysis are, firstly, to quantitatively ascertain the factors that influenced route selection using least-cost path (LCP) modelling and, secondly, to identify the primary reasons for substantial disparities between known old routes and the best performing LCPs.

The study region consists of two sections. The smaller, western section comprises the fluvial terraces of the River Rhine and a 5-kilometre hilly fringe. Moving eastwards from the Rhine, these elevations climb from 42 to 660 metres above sea level. In contrast to the relatively flat fluvial terraces of the Rhine, which were inhabited in prehistoric times, the hilly eastern part of the study region contains few archaeological remnants predating the Middle Ages.[2] This paucity is likely due to less fertile

1 *Nicke,* Brüderstraße (2000); *Nicke,* Wege (2001); *Nicke,* Heidenstraße (2001).
2 *Herzog*, Issues (2022), 134.

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soils, cooler temperatures, higher precipitation rates, and steeper slopes – all of which hinder efficient agriculture.

It appears that, for a significant duration of time, most medieval and early modern roads remained in use, with some being adapted to new requirements, and new roads emerging as new locations gained importance. Regrettably, determining the age of the Nicke roads is seldom possible due to the absence of archaeological investigations and historical sources. Hans Leonhard Brenner postulates that some of the old pathways described by Nicke had prehistoric predecessors (cf. Table 11.1).[3] He contends that the presence of individual prehistoric sites near a route indicates the route's significance during that time. This assumption forms the basis of many LCP studies. However, both old maps[4] and statistical tests[5] suggest that this hypothesis may not hold true in every situation. In this study area, no Roman roads have been documented. According to Reinhold Wacker, during the Merovingian era, travellers primarily used Roman roads and pack animals were the preferred mode of transport, while wheeled vehicles were mainly employed for agricultural purposes.[6] During the Carolingian era, the road system expanded into areas east of the Rhine, with Cologne serving as one of the primary points of origin for this expansion.[7] Some authors propose that this development began during the Merovingian period.[8] Consequently, roads commencing in Cologne or Siegburg – and mentioned in medieval historical sources or depicted on early modern maps – are often presumed to have been constructed in the early Middle Ages.

In the study region, medieval roads were typically formed and maintained through daily usage, with some exceptions being bridges and paved fords.[9] Many clusters of sunken lanes, predominantly found in wooded areas, serve as archaeological evidence of medieval and early modern road systems. These sunken lanes – also known as "hollow ways" – come into existence when soil must be cleared due to heavy vehicles repeatedly getting stuck in the mud.[10] Consequently, embankments are formed on both sides of the pathway. On slopes, rainwater erosion can wear away any remaining soil on the track. Occasionally, to avoid muddy tracks, new pathways were established parallel to existing ones. This practice explains why bundles of sunken lanes are frequently encountered.

Medieval and early modern roads in the studied region were designed to be as direct as possible, generally following ridges and attempting to circumvent water-

3 *Brenner*, Straßen (2016), 11.
4 E.g. Mercator, Grundtliche Beschreibungh. Ed. *Weirich*.
5 *Herzog*, Testing Models (2014).
6 *Wacker*, Verkehrswesen (2008), 37–38.
7 *Wacker*, Verkehrswesen (2008), 39.
8 E.g. *Berges*, Eisenstraße (2016), 24.
9 *Nicke,* Wege (2001), 14.
10 *Brenner*, Straßen (2016), 11; *Nicke,* Wege (2001), 14.

Table 11.1: Old road sections in the study area.

No.	Road name	Length (m)	References (route)	Waypoints	Date
1	Bergische Eisenstraße	45275	Nicke, Wege (2001), 106–109; map p. 102; Berges 1993	Remscheid-Bergisch Born, Wipperfürth, Marienheide, Gummersbach, Drolshagen-Gelslingen	Nicke, 102, 178: high to late Middle Ages; Berges: fourteenth century
2	Bergische Eisenstraße, alt. route III	10521	Nicke, Wege (2001), 109	Gummersbach-Bernberg, Bergneustadt-Belmicke	Nicke, 102, 178: high to late Middle Ages
3	Brüderstraße	45634	Nicke (2000); Brenner (2016); Wacker (2008), 41	Bergisch Gladbach-Frankenforst, Reichshof-Erdingen	Nicke, 210: late Iron Age; Brenner: since Roman times; Wacker: Carolingian
4	Heerweg	37948	Nicke, Wege (2001), 85, map p. 78; Brenner (2016)	Bergisch Gladbach, Wipperfürth, Halver	Brenner: Neolithic
5	Heerweg II	20333	Nicke, Wege (2001), 87–88	Bergisch Gladbach-Romaney, Lindlar-Buchholz	
6	Heidenstraße	53683	Nicke, Heidenstraße (2001), 35–48; Brenner (2016); Gaudich (2016); Scherer (2016); Wacker (2008), 69	Bergisch Gladbach-Frankenforst, Hohkeppel, Marienheide-Gimborner Galgen, Meinerzhagen-Vestenberg	Brenner: Neolithic; Gaudich: Protohistory; Berges: since about 1000; Wacker: medieval
7	Hileweg	26274	Nicke, Wege (2001), 49–50; map p. 45	Drolshagen-Wegeringhausen, Halver	Nicke, 52: early medieval?
8	Homburgische Eisenstraße	21766	Nicke, Wege (2001), 109; map p. 102	Engelskirchen, Gummersbach-Derschlag	Nicke, 102, 178: high to late Middle Ages
9	Köln-Dortmunder Straße	22168	Nicke, Wege (2001), 83, map p. 78; Wacker (2008), 68	Leverkusen-Neuboddenberg, Remscheid-Bergisch Born, Remscheid-Lennep	Wacker: thirteenth century
10	Märkische Eisenstraße	14350	Nicke, Wege (2001), 104; map p. 102	Meinerzhagen-Schnüffel, Lüdenscheid-Bierbaum	Nicke, 102, 178: high to late Middle Ages
11	Mauspfad	17896	Nicke, Wege (2001), 42–43; map p. 71; Brenner (2016)	Siegburg, Köln-Heumar	Brenner: Neolithic

Table 11.1 (continued)

No.	Road name	Length (m)	References (route)	Waypoints	Date
12	Nutscheid	36377	Nicke, Wege (2001), 80–82; map p. 59	Hennef-Schloss Allner, Reichshof-Eichholz	
13	Oberbergische Diagonale, southern route	16933	Nicke, Wege (2001), 116–117	Wiehl-Jägerhof, Reichshof-Hespert	
14	Polizeiweg	44789	Nicke, Wege (2001), 115; map p. 88; Scherer (2016)	Siegburg, Hohkeppel, Wipperfürth	
15	Zeitstraße	58334	Nicke, Wege (2001), 89–96; map p. 88; Berges (1993)	Siegburg, Much, Marienheide, Halver	Berges: since about 1000 (section Much to Marienheide)
16	Zeitstraße, alt. route 1	12425	Nicke, Wege (2001), 92	Much, Oberfrielinghausen/ Heidenstraße	
17	Zeitstraße, alt. route 2	6670	Nicke, Wege (2001), 94–95	Gummersbach-Birnbaum, Gimborner Galgen/Heidenstraße	
18	Zeitstraße, access from Gummersbach	5738	Nicke, Wege (2001), 95–96	Gummersbach-Birnbaum, Gummersbach	

courses, which were often surrounded by marshy areas, impeding swift movement.[11] The layer of soil on these ridges was rather thin, and wheeled vehicles gradually eroded it, keeping the roads relatively dry. Over time, the road network evolved, particularly with the increasing significance of the iron industry in the valleys.[12] As a result, more construction activity focused on roads in wet areas. This development culminated in the Industrial Revolution, which reached its zenith in the nineteenth century.

According to Nicke, pack animals were likely the swiftest mode of transportation on most routes prior to road construction commencing in the late eighteenth century. Oxcarts were primarily used for short-distance transport, while pack animals were preferred for longer journeys.[13] Two-wheeled horse carts gained popularity as a

11 *Nicke,* Brüderstraße (2000), 25, 32–33; *Nicke,* Wege (2001), 7–9; *Berges*, Eisenstraße (2016), 30; *Brenner*, Straßen (2016), 11.
12 *Nicke,* Wege (2001), 10–11; *Geurts*, Verkehrsentwicklung (2016), 30.
13 *Nicke,* Wege (2001), 21.

means of transport during the seventeenth and eighteenth centuries. In the hilly study area, the introduction of wheeled transport on routes previously utilised exclusively by pedestrians, pack animals and occasional riding animals necessitated specific alterations. The critical slope – which indicates the point at which using hairpin curves becomes more efficient than the direct uphill or downhill route – is higher for pedestrians than for wheeled vehicles. The physiologist Alberto Minetti discovered that the critical slope for pedestrians is approximately 25% for both descending and ascending paths.[14] Roman roads and modern forest roads typically maintain slopes below 12%, with only brief sections exceeding this value.[15] After vehicles gained popularity, these now dictated the road's trajectory in areas of steep slopes, even though most travellers still walked, and pack animals handled the bulk of transportation, Sunken lanes were mainly formed by vehicles. Thus, most of the routes described by Nicke were probably utilised by wheeled vehicles for an extended period.

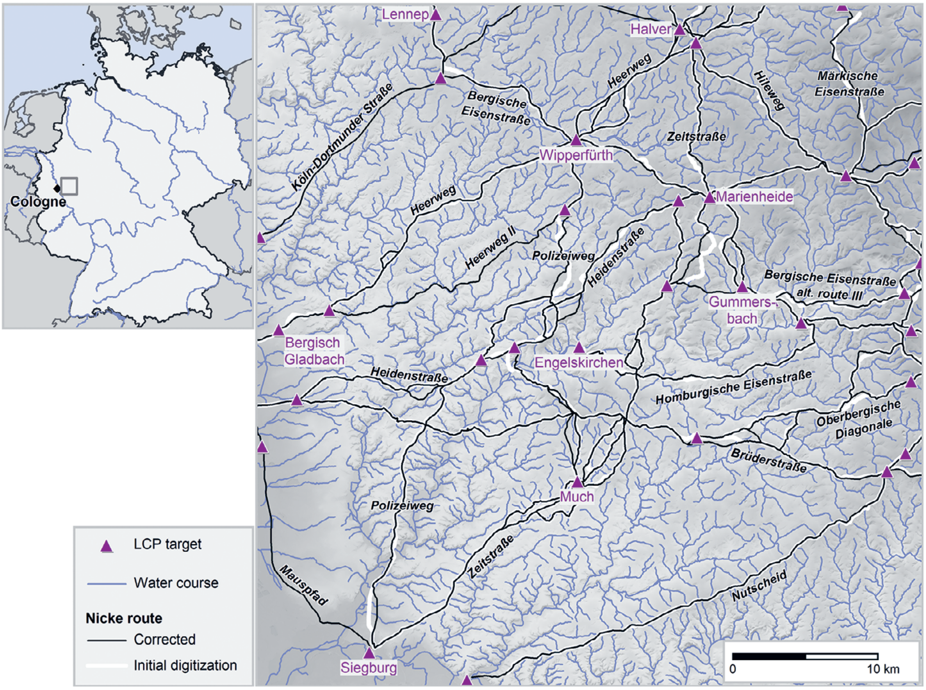

Figure 11.1: Depiction of the study area, covering 2107 square kilometres, with a dense network of mostly small watercourses. It shows the digitisation of the roads published by Nicke (initial digitisation used in previous studies plus a new updated version), as well as the LCP (Least-Cost Path) targets used in this paper.

14 *Minetti*, Gradient (1995), 1699–1700.
15 E.g. *Cretu/Rusnac*, Forest Roads (1998); *Grewe*, Wege (2004), 30.

The roads documented by Nicke in the study area (see Figure 11.1) were digitised using a Geographic Information System (GIS). Research published previously focused on identifying and quantifying the parameters of historical movement patterns in the study region.[16] This was accomplished by employing LCP algorithms to reconstruct the known roads. By stepwise introducing the cost factors slope, crossing watercourses, and traversing wet areas, I attempted to identify the cost model that most accurately replicated the known old roads. Model performance was assessed by calculating the total percentage of LCPs within the buffered Nicke roads (buffer radius: 200 metres). For the nineteen Nicke road sections considered, the best-performing and most refined model achieved a performance of 68%. The individual replication rates ranged from 25% to 100% and, for eleven road sections, less sophisticated cost models outperformed the overall top-performing model. This article delves into the reasons behind these unexpected outcomes.

In the first step, the reliability of the digitised Nicke roads was checked and corrected using several approaches. The initial digitisation of the roads was mainly based on two out of three nineteenth century map sets provided in the Web Map Services (WMS) of the Ordnance Survey Institute of North Rhine-Westphalia in Germany (Geobasis NRW),[17] which often show a denser network of roads and paths than recent maps. This – coupled with some missing equivalents to Nicke road sections on these nineteenth-century maps – complicates the digitalisation.[18] A re-examination of Nicke's texts led to both alterations and the identification of additional road sections omitted in the initial digitisation. This verification process also involved two supplementary sets of digitised historical routes: (1) independent digitisation of Nicke roads by Markus Mertens and (2) the freely available digital roads of the Viabundus project.[19] Additionally, routes depicted on old maps and sunken lanes visible in Airborne Laser Scanning (ALS) data were taken into account whenever the initial digitisation substantially differed – either from the independent digitisation by Mertens or the Viabundus roads. Based on the assumption that the pre-industrial road system had not changed significantly, the following maps created before 1800 (and which cover parts of the study area) were considered when checking the Nicke roads: the Mercator map,[20] the

16 *Herzog*, Issues (2022). In what follows, I will use the term SDH study to refer to this publication.

17 The earliest set of nineteenth century map sheets covering part of the study area were created between 1817 and 1828. These maps go back to Tranchot and von Müffling, but were rarely considered due to their limited coverage and lower accuracy compared to the second set of maps, known as "Uraufnahme", dating from around 1845. The third set ("Neuaufnahme") was produced approximately fifty years later. "Uraufnahme" and "Neuaufnahme" cover the entire study area.

18 Additional issues include roads ending at the edge of a map sheet and map distortions (mainly near the edges of the "Uraufnahme" map sheets). The corresponding WMS provides rectified map sheets, improved during the project. The original digitised roads often no longer coincide with the lines shown on the rectified WMS map.

19 *Holterman* et al. (Ed.), Viabundus (2022).

20 Mercator, Grundtliche Beschreibungh. Ed. *Weirich*.

Waye map,[21] the Ploennies maps[22] and the map of the territory of Gimborn-Neustadt published by Nehls.[23] The corrected Nicke roads were aligned with modern roads wherever possible, assuming that the modern road is a successor to an earlier route and that LCPs tend to be attracted to modern roads anyway. Figure 11.1 displays the corrected digitisation of trade roads in the study area. New LCP targets were selected either near the edges of the study area or at locations where a Nicke road changes its general direction (Table 11.1).

The next section illustrates the process of checking the digitised Nicke roads by presenting and discussing the course of two segments of the old road known as Brüderstraße. The state-of the-art LCP methodology is then introduced. In what follows, I present the LCP results for the corrected Nicke roads, and investigate the impact of road section attributes – such as length or mean slope – on the LCP's replication performance. Finally, the discussion of the old road sections with low replication performance identifies several reasons for this outcome.

11.2 Brüderstraße – the road of the friars

This section discusses the challenges associated with digitising historical roads by focusing on the Brüderstraße, connecting Cologne with Siegen. Nicke's extensive documentation of this route includes references to historical sources as well as descriptions of settlements and landmarks along the road.[24]

According to Nicke, the name "Brüderstraße" (referred to as "die alde broeder straisse" at the time) was first documented in 1464.[25] The earliest historical sources mentioning the existence of this road date back to the first half of the fourteenth century.[26] Nicke assumes that the Brüderstraße had a late Iron Age predecessor.[27] Brenner, on the other hand, believes that this road has existed since Roman times.[28] Wacker refers to a Carolingian road that linked Cologne with the Siegen area.[29] The Brüderstraße is one out of two roads shown on the earliest map depicting roads in the study region – this map was created in 1500 by Erhard Etzlaub.[30]

21 Van der Waye/van der Waye, Eigentliche Description. Ed. *Weirich*.
22 Ploennies, Topographia. Ed. *Dietz*.
23 *Nehls*, Täler (1996), frontispiece.
24 *Nicke,* Brüderstraße (2000).
25 *Nicke,* Brüderstraße (2000), 15, 209. The attribute "alde" (i.e. old) signifies that the road already had a long tradition at that time.
26 *Nicke,* Brüderstraße (2000), 13.
27 *Nicke,* Brüderstraße (2000), 210.
28 *Brenner*, Straßen (2016), 13.
29 *Wacker*, Verkehrswesen (2008), 41.
30 *Berger*, Karten (2021), 9.

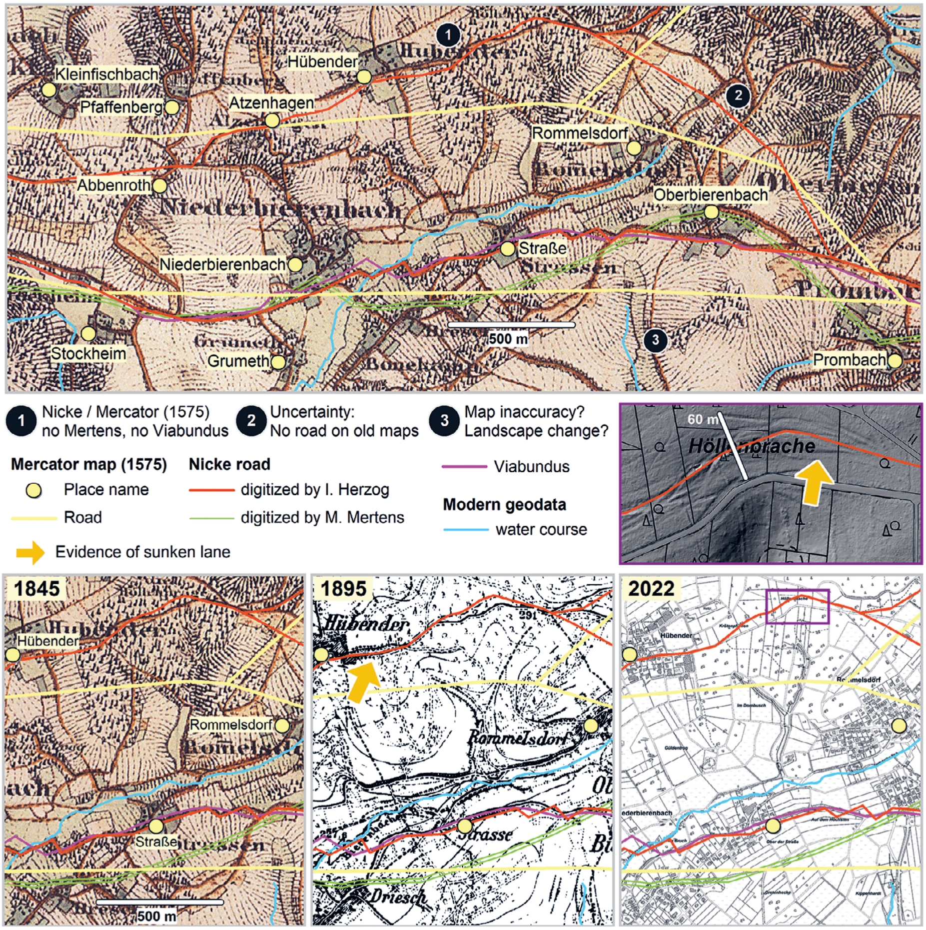

Figure 11.2: Digitalisation of two variants of a Brüderstraße section based on historical maps and ALS data, cross-referenced with Viabundus and an alternative digitalisation by Markus Mertens. Background maps were provided by Geobasis NRW.

The study area covers only a portion of the Brüderstraße, extending from Bergisch Gladbach-Frankenforst in the west to Reichshof-Erdingen in the east, with a digitised road length of nearly 46 kilometres. Figure 11.2 illustrates the process of checking the accuracy of the digitised Nicke road segments. The map at the top of Figure 11.2 displays two variants of a Brüderstraße segment, with the "Uraufnahme" map serving as a background reference. According to Nicke, the earlier variant passed through Abbenroth and Hübender, proceeding north of Rommelsdorf.[31] For the alternative later variant, Nicke lists the place names Stockheim, Grumeth, Niederbierenbach, Straße,

31 *Nicke*, Brüderstraße (2000), 39.

and Oberbierenbach. In Nicke's view, these two variants converge approximately 500 metres east of Oberbierenbach. Nicke's earlier variant is also depicted on Mercator's map;[32] however, it is neither included in the Nicke road digitisation by Mertens, nor in Viabundus. East of Hübender, sunken lanes along a bend can be observed in the ALS data, providing additional evidence of an old road (Figure 11.2). The sunken lane bundle spans approximately 60 metres. Unfortunately, these sunken lanes do not extend in an easterly direction, and no nineteenth-century map displays a road corresponding to Nicke's description of the road segment leading to the junction east of Oberbierenbach. Consequently, the digitised road segment may significantly deviate from the route Nicke had in mind. Similar issues have been encountered multiple times, resulting in varying levels of accuracy in the digitised Nicke roads, even in the corrected dataset. Another issue is the differences between the modern and nineteenth-century depictions of the watercourses (e.g. no. 3 in Figure 11.2), caused by changes in the landscape or inaccuracies in the maps. These differences complicate the digitisation of potential ford locations based on the old maps. Similarly, those roads digitised according to historical maps often do not coincide with modern roads due to changes in the road infrastructure (such as the introduction of roundabouts) or errors in the original maps.

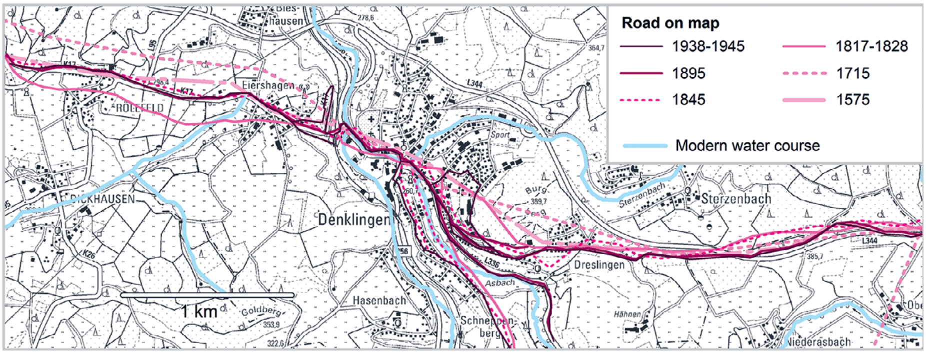

Figure 11.3: Brüderstraße: roads digitised from historical maps in the area of Reichshof-Denklingen. Background: a recent map provided by Geobasis NRW.

This issue is further illustrated in Figure 11.3, which was created with the objective of identifying the locations where the early modern Brüderstraße crossed the watercourses in the Reichshof-Denklingen area. Denklingen is located approximately four kilometres west of Erdingen, the easternmost waypoint of the Brüderstraße included

32 Mercator, Grundtliche Beschreibungh. Ed. *Weirich*. The roads on the map dated 1575 were manually transferred to a modern map by connecting waypoints, resulting in long straight-line segments with limited accuracy.

in the study area. According to Nicke, the Brüderstraße crosses two watercourses separately that converge west of the centre of Denklingen.[33] However, the roads depicted on the available nineteenth-century maps intersect with the combined watercourse to the north of the confluence point. Ploennies's map sheet of the Windeck administrative unit[34] displays only one of the watercourses, and it suggests that the old road passed to the north of the church, implying that it intersected the joint watercourse. According to Mercator[35], the Brüderstraße crosses the watercourse to the north of the confluence but to the south of the church – a boundary is also depicted to the south of the confluence, crossing both streams. In medieval and early modern times, a path along a boundary was commonly established to ensure that all relevant individuals were aware of the demarcation.[36] Thus, probably an older alternative path existed south of the main Brüderstraße in 1575. This path is challenging to reconstruct within the built-up area of Denklingen, which includes a railroad line set up in the early twentieth century. This is not the only case where contemporary landscape changes complicate accurate reconstruction of the Nicke roads in the study area. For instance, the western portion of the Brüderstraße is impacted by a motorway.

11.3 Computing LCPs

Past and present roadways often deviate from straight lines, implying that factors beyond simple map distance influenced route selection. Estimates of daily travel distances during the Middle Ages[37] provide only a starting point for determining the cost of travel several centuries ago. The underlying assumption in many LCP studies is that historical roads were designed or evolved to minimise travel costs. Nicke shares this viewpoint, suggesting that crafting the final route required years of experience and a deep understanding of the landscape.[38] Identifying the parameters leading to the most accurate LCP replication of known historical routes offers new insights into contemporary mobility patterns. This is one of the reasons why archaeologists have frequently employed LCP calculations.[39] State-of-the-art LCP methodology between a starting and destination point[40] is outlined in Figure 11.4, though with some simplification.

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33 *Nicke,* Brüderstraße (2000), 51.
34 Ploennies, Topographia. Ed. *Dietz*, map no. 15.
35 Mercator, Grundtliche Beschreibungh. Ed. *Weirich.*
36 *Rutz*, Beschreibung (2018), 151–167.
37 E.g. *Nicke,* Wege (2001), 22; *Ohler*, Reisen (Mittelalter) (2009).
38 *Nicke,* Brüderstraße (2000), 52.
39 For references, see *Herzog,* Spatial analysis (2020).
40 *Herzog,* Spatial analysis (2020). Computing least-cost networks, that link several locations, is more complex, see *Herzog,* Networks (2013).

A large majority of the archaeological LCP studies employ cost models that factor in slope-dependent cost functions, based on slope data derived from a digital elevation model (DEM). Figure 11.4 (box "Input") displays a tiny and simple raster DEM with altitudes descending in a northerly direction. The quality of the DEM depends on its resolution and accuracy.[41] Many LCP algorithms require DEMs with square raster cells, but the cells of the popular ASTER and SRTM DEMs are rectangular. High-resolution DEMs more accurately model the deeply incised valleys. Lower resolution DEMs tend to smooth the terrain, causing modern features like roads and buildings to appear less pronounced. Furthermore, the LCP calculation effort increases inversely with the area of the DEM grid cell. Therefore, the highest resolution DEM available may not be the ideal basis for slope-dependent LCP calculations. For the study area, highly precise elevation data with a 25-metre resolution was provided by Geobasis NRW. The explanation of the methodology shown in Figure 11.4 uses a DEM with 100-metre cells, as this simplifies the calculations involved.

A path within a raster grid, such as the DEM, is constructed through links connecting adjacent raster cells (Figure 11.4, box "Grid to graph conversion"). The drawback of this method is that an error-free reconstruction of a straight-line path is only possible if the path runs in the direction of one of the adjacent cells considered. Figure 11.4, box "Neighbour number", illustrates the pros and cons of increasing the number of neighbours considered. For the sake of simplicity, the example in Figure 11.4, box "Grid to graph conversion", shows only the links to the eight nearest neighbours. However, the software employed in reconstructing the Nicke roads incorporates links to forty-eight neighbours, with longer links subdivided to ensure appropriate costs for traversing high-cost barriers.[42] Even with this complex implementation, the worst-case difference between the computed and the true optimal path remains at 8% of the actual path length.

Most GIS software includes procedures for computing slope raster grids. When utilising a slope-dependent cost component reliant solely on such a slope grid, the direction of cell traversal is disregarded. But it is crucial to consider the direction of travel.[43] The approach presented in Figure 11.4, box "Computing link weights", "Slope (percent)", tackles this problem by computing the slope of a path traversing a raster cell from the raster DEM.

Figure 11.4, box "Slope-dependent costs", displays various slope-dependent cost functions applied in archaeological research.[44] Assuming that the old roads were used with similar frequency in both directions, the costs for moving uphill and downhill

41 A discussion of issues encountered when creating LCPs based on elevation data is also found in *Verhagen/Nuninger/Groenhuijzen*, Pathways (2019), 227–228.

42 For details, see *Herzog*, Spatial analysis (2020).

43 For the slope that is actually experienced when traversing a grid cell, the term *effective slope* is used (*Conolly/Lake*, GIS [2006], 292).

44 For references, see *Herzog*, Spatial analysis (2020).

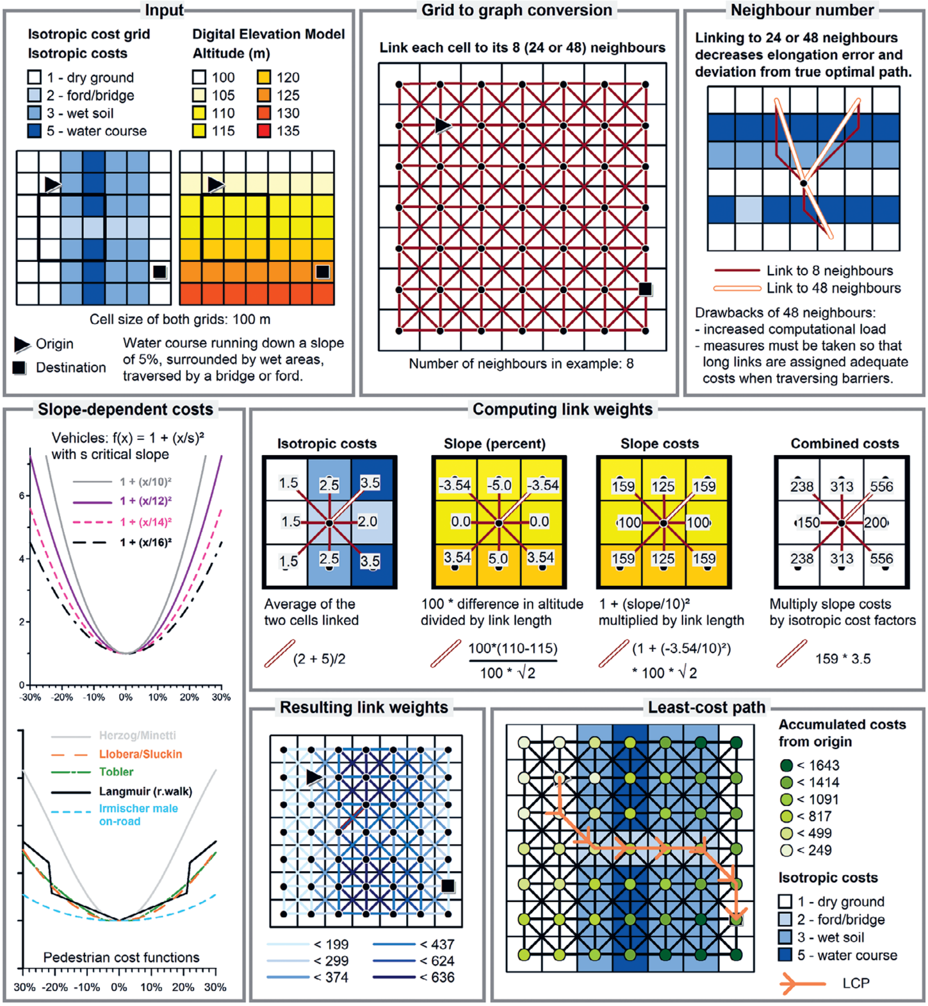

Figure 11.4: Simplified LCP methodology.

are averaged, resulting in symmetric cost functions. The pedestrian cost functions estimate either time (Figure 11.4, box "Slope-dependent costs": Tobler; Langmuir (r. walk); Irmischer male on-road)[45] or energy expenditure (Figure 11.4, box "Slope-dependent costs": Herzog/Minetti; Llobera/Sluckin).[46] Each cost function has been standardised to assign a cost of one unit for a selected distance unit when moving on

45 *Tobler*, Geographic modeling (1993); *Langmuir*, Mountaincraft (³2004), 40; *Irmischer/Clarke*, Speed (2017), 5–6.
46 *Herzog*, Cost Functions (2013), 377; *Llobera/Sluckin*, Zigzagging (2017), 210.

level terrain, thus facilitating the comparison of the impact of slope on costs. For instance, the estimates provided by Irmischer's male on-road cost function for steep slopes are much lower than those given by the Herzog/Minetti cost function.

Due to the considerable variation in wheeled vehicles used in the past, it is challenging to identify plausible cost curves.[47] The class of generic quadratic cost functions with a critical slope parameter offers more reasonable cost estimates for vehicle movements than functions derived from measurements of pedestrians (Figure 11.4, box "Slope-dependent costs", Vehicles).[48] For the sake of simplicity, Figure 11.4 (box "Computing link weights") employs a vehicle cost function with a critical slope of 10% to estimate slope costs.

When selecting a cost function, it is advisable to reference the original publication to minimise the risk of introducing errors.[49] The SDH case study presents the results of systematic tests of slope-dependent cost functions, revealing that the quadratic vehicle cost function with a critical slope of 17% yields the most accurate replications of the Nicke roads. The use of two-wheeled vehicles, which can generally handle steeper slopes compared to four-wheeled vehicles, is the likely reason for the discrepancy to the critical slope of the Roman roads and modern forest roads discussed in the Introduction.[50] Figure 11.4, box "Input", outlines an approach for modelling penalties for watercourses and wet areas by utilising an isotropic cost grid. The slope costs are multiplied by the penalties saved in the isotropic cost grid (Figure 11.4, box "Computing link weights"). In this simplified model, the penalty factor for traversing watercourses is five, for wet soils three, and for possible ford locations two; however, for the SDH study, systematic testing identified different factors that yielded the best-performing cost model for replicating Nicke roads. These values include twenty-five for watercourses wider than 3 metres, ten for smaller watercourses, four for wet areas, and 1.7 for ford locations. The watercourse and soil data were obtained from state organisations, while ford or bridge locations were digitised from nineteenth-century maps. Buffering of watercourses is essential to prevent the LCPs from crossing them without incurring additional costs.

47 See *Verhagen/Nuninger/Groenhuijzen*, Pathways (2019), 220.

48 *Llobera/Sluckin*, Zigzagging (2017), 209–210.

49 For instance, there has been some confusion about units of measurement in several archaeological publications presenting or applying slope-dependent cost functions. This applies for the popular slope-dependent hiking function originally published by *Tobler,* Geographic modeling (1993), which is neither correctly copied by *Wheatley/Gillings*, Spatial Technology (2002), on p. 155 nor by *Conolly/Lake*, GIS (2006), on p. 219. Moreover, a formula may be misprinted, e.g. Tobler's formula in *Batten*, Pathways (2007), 170. According to *Tobler,* Geographic modeling (1993), the hiking function was estimated from empirical data given by *Imhof,* Gelände (1950), 217–220. But *Herzog,* Cost Functions (2013), revealed relevant differences between *Imhof*'s and *Tobler*'s time estimates.

50 *Nicke,* Brüderstraße (2000), 199–201. *Burmeister*, Wagen (2004), points out on p. 25 that two-wheeled carts are better suited for hilly terrain.

After establishing the graph of linked neighbouring cells with weights representing the combined isotropic and slope costs (Figure 11.4, box “Computing link weights”), the LCP is computed by applying Dijkstra’s algorithm.[51] Starting from the origin, this spreading algorithm successively calculates the minimum accumulated costs of movement to each grid cell until the destination is reached. Additional raster grids store the accumulated costs for each cell (Figure 11.4, box “Least-cost path”) and the link to the previous cell in the spreading process. The LCP is derived from the accumulated cost grid by backtracking from the destination to the origin, connecting the backlinks. Alternative, less reliable LCP methods are nowadays outdated: these include Tomlin’s algorithm, steepest descent approaches (instead of backlinks), or the push-broom method.[52]

Compared to the early days of archaeological LCP applications, most researchers now have access to more precise and higher-resolution topographic data, as well as faster computers with greater memory capacity, and more reliable implementations of LCP algorithms for graphs. However, the number of neighbouring cells considered in the grid-to-graph conversion step is often still inadequately limited to eight. Moreover, the selection of a suitable cost model remains a challenge. Publications providing cost estimates for pack animal transport, riding animals, and water travel are scarce and may not be readily transferable to diverse landscapes and modes of transport. Furthermore, nearly all walker cost models disregard variations in travel costs due to gender, age, weight, load, and the fitness of the walker, as well as the number of travellers in the pedestrian group. For both walkers and vehicles, factors like vegetation, climate, seasonality, and weather influence travel times and energy expenditure. For vehicles, the risks of loss of traction or catastrophic overturning are not included in the model. While some of these issues may be addressed in future developments, all LCPs are and will continue to be computed based on simplified models of past reality. In this context, Eve and Crema remind us of two important quotes regarding models in general: “All models are wrong, but some are useful. A ‘true model’ is in this sense an oxymoron”.[53]

By gradually introducing new factors, the SDH study generated more complex and more accurate cost models of past movement patterns in each step. Initially, the best performing slope-dependent cost function was selected, resulting in a performance indicator of nearly 57%. When barriers for rivers were incorporated, performance improved to almost 63%. As mentioned above, the final model, which included all the listed factors, yielded a performance indicator of 68%, with individual replication rates ranging from 25% to 100%. This means that a cost model reconstructing one Nicke road section well does not guarantee successful replications for other Nicke road sections. Another issue warranting further investigation was the fact that less refined cost models outperformed the overall best performing model for several Nicke road sections.

51 *Dijkstra*, Note (1959).
52 *Conolly/Lake*, GIS (2006), 221–223, 252–254.
53 *Eve/Crema*, House (2014), 272.

After correcting and supplementing the Nicke roads, waypoints were introduced close to the border of the study area, at points where these roads changed direction or where multiple roads converged and shared the same route for some distance. This division resulted in thirty-six road sections with a combined length of 528 kilometres. Omitting sections that offered shorter alternative routes, twenty-eight sections covering 497 kilometres were chosen for generating LCPs. Considering that a significant portion of the corrected Nicke roads coincided with modern roads, the performance indicator was adjusted by reducing the radius of the Nicke roads' buffer to 100 metres.

11.4 LCP results for corrected Nicke roads

Table 11.2 lists the twenty-eight Nicke road sections mentioned above in the same order as Table 11.1, with the additional waypoints considered. For each road section, LCPs were generated based on four cost models M1 to M4 that increase in complexity, with M1 depending only on slope, M2 including an additional penalty for traversing rivers (width greater than 3 metres), M3 introducing penalties for minor watercourses, and finally, M4 also taking into account higher friction costs in wet areas but reducing costs at ford or bridge locations depicted on the "Uraufnahme". The parameters of the models were selected based on the results of the SDH study outlined in the section 'Computing LCPs'.[54] In Table 11.2, the performance indicators are given in columns M1 to M4. The M1- and M4-LCPs are shown in Figure 11.5.

Table 11.2: Road section attributes and performance of the LCPs generated based on the four cost models M1 to M4.

Road name	Length (m)	Detour factor	Elevation range (m)	Mean slope	Confirmed (%)	M1	M2	M3	M4	Best %	Best M
Bergische Eisenstraße, west	11805	1.14	87	8.8	100.0	15	6	16	16	16	M3
Bergische Eisenstraße, Marienheide-Wipperfürth	10733	1.07	148	7.6	100.0	38	38	62	66	66	M4

54 Buffers of twenty metre radius were created for watercourses, wet areas, and ford or bridge locations, to ensure that LCPs traversing them incur the due costs.

Table 11.2 (continued)

Road name	Length (m)	Detour factor	Elevation range (m)	Mean slope	Confirmed (%)	M1	M2	M3	M4	Best %	Best M
Bergische Eisenstraße, Marienheide-Gummersbach	8759	1.33	146	12.4	42.2	45	45	58	70	70	M4
Bergische Eisenstraße, east	13978	1.16	260	13.9	85.6	38	43	65	77	77	M4
Bergische Eisenstraße, alt. route III	10521	1.15	240	14.7	89.9	57	60	66	73	73	M4
Brüderstraße	45634	1.11	347	9.8	100.0	49	49	58	54	58	M3
Heerweg, south	26575	1.09	233	7.1	100.0	89	89	87	93	93	M4
Heerweg, north	11373	1.09	150	7.7	71.3	36	48	45	44	48	M2
Heerweg II	20333	1.14	182	10.6	1.0	22	22	29	50	50	M4
Heidenstraße, west	15193	1.17	176	8.4	58.4	6	6	47	50	50	M4
Heidenstraße, Hohkeppel-Gimborner Galgen	19642	1.12	182	10.9	61.8	40	40	71	67	71	M3
Heidenstraße, east	18847	1.14	185	10.5	66.4	59	59	59	71	71	M4
Hileweg	26274	1.13	146	10.6	79.7	39	39	59	53	59	M3
Homburgische Eisenstraße	21766	1.30	200	13.3	11.9	8	8	32	14	32	M3
Köln-Dortmunder Straße, south	17434	1.05	193	6.2	100.0	97	97	90	90	97	M1
Köln-Dortmunder Straße, north	4734	1.07	39	5.9	100.0	62	62	62	62	62	M4
Märkische Eisenstraße	14350	1.20	163	9.7	0.0	47	47	44	52	52	M4
Mauspfad	17896	1.12	49	3.2	26.3	6	8	12	14	14	M4

Table 11.2 (continued)

Road name	Length (m)	Detour factor	Elevation range (m)	Mean slope	Confirmed (%)	M1	M2	M3	M4	Best %	Best M
Nutscheid	36377	1.08	378	6.9	90.2	8	94	85	94	94	M4
Oberbergische Diagonale, southern route	16933	1.11	224	9.2	92.7	39	56	64	68	68	M4
Polizeiweg, south	23859	1.12	195	5.7	51.7	14	68	72	70	72	M3
Polizeiweg, north	20930	1.26	208	10.0	48.1	22	24	36	63	63	M4
Zeitstraße, south	19134	1.06	170	6.6	68.4	71	71	69	71	71	M1
Zeitstraße, Much-Marienheide	26610	1.21	263	12.0	44.3	47	59	26	24	59	M2
Zeitstraße, north	12589	1.17	124	10.1	1.8	60	60	71	24	71	M3
Zeitstraße, alt. route 1	12425	1.21	251	11.9	0.0	22	22	37	28	37	M3
Zeitstraße, alt. route 2	6670	1.12	143	18.8	4.8	98	44	100	91	100	M3
Zeitstraße, access from Gummersbach	5738	1.09	107	11.1	100.0	91	91	91	36	91	M1

The new outcomes – based on the corrected and supplemented Nicke roads – are quite similar to the results of the SDH study. Using the 100-metre buffer criterion, the best performing model M4 has a large range of success: 14 to 94% (Table 11.2). For fourteen out of twenty-eight road sections, less refined cost models outperform the overall best performing model. This shows that the errors and omissions of the Nicke road set used in the SDH study did not substantially impact the replication performance. Consequently, the reasons for the varying performance of the different cost models must be sought elsewhere. Therefore, the characteristics of the Nicke roads listed in Table 11.2 are examined for their impact on the replication performance of the LCPs. The probability of such an impact is investigated below using statistical approaches.[55]

55 The computations were performed using the PAST software, see *Hammer*, Past 4 (2023).

In Table 11.2, the “Length (m)” column refers to the length of the digitised Nicke road section considered. It seems obvious that by introducing additional waypoints – and thus subdividing the road sections – the LCPs are forced to run closer to the Nicke road. But in the study area, the length of the Nicke road section has little effect on the success of the LCPs in replicating the Nicke roads. The Pearson correlation coefficient[56] between the length of the Nicke road section and the corresponding M4-LCP performance is 0.11, with a probability of 0.57 (i.e. 57%) that the two variables are uncorrelated. The scatterplot of these variables does not suggest a non-linear relationship.

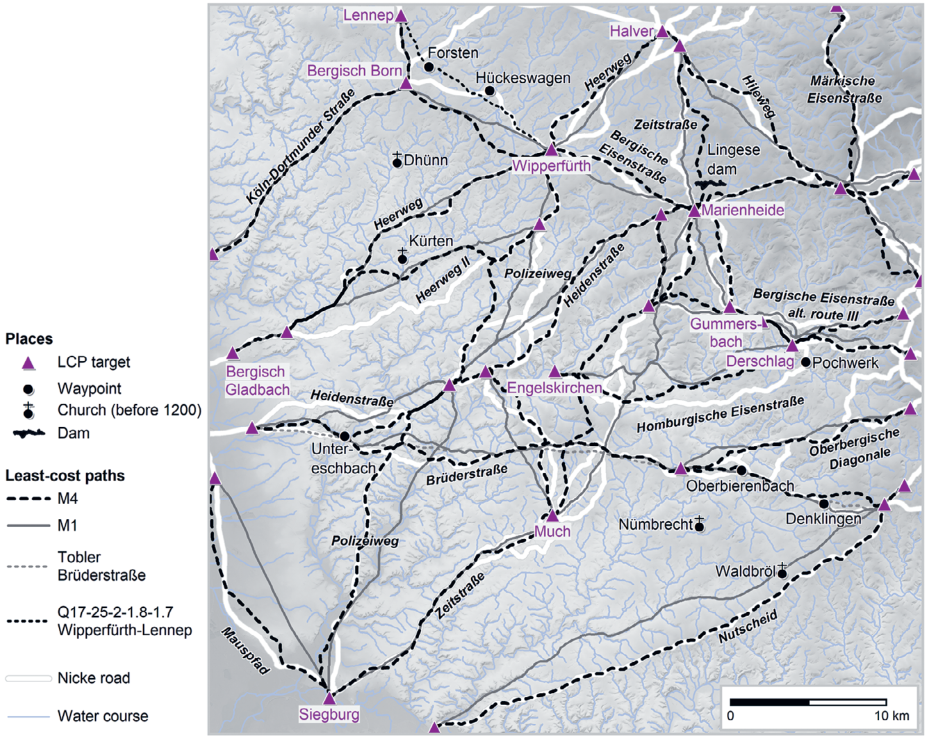

Figure 11.5: Selected LCPs computed aiming to reconstruct Nicke roads.

The “Detour factor” in Table 11.2 represents the length of a road section divided by the straight-line distance connecting the starting and ending points of that section. A higher detour factor indicates that the road section is longer compared to the direct

56 The coefficient is explained for instance by *Conolly/Lake*, GIS (2006), 151 and by *Shennan*, Quantifying (^{2}1997), 140.

distance.[57] The negative correlation coefficient of -0.37 between the detour factor and the performance of M4-LCPs suggests that M4-LCPs tend to better reconstruct fairly direct road sections compared to those that significantly deviate from a straight-line path.

In Table 11.2, the column labelled "Elevation range (m)" displays the difference between the maximum and minimum altitude values encountered when travelling along the Nicke road. This variable exhibits a correlation not only with the performance of M4-LCPs (0.36) but also with the length of the road section (correlation: 0.71). The latter observation is unsurprising, given that most road sections in this study are roughly west-to-east connections within a landscape that generally features increasing altitudes in this direction.[58]

The average slope of the road sections was derived from a slope map, expressed in percentages. While the LCP algorithm considers effective slope, the slope map provides information about the steepness of the terrain at each raster cell. Surprisingly, Table 11.2 reveals higher mean slope values than average for several sections of Eisenstraße roads. The German term "Eisenstraße" indicates that these roads were used for transporting iron or iron ore. Constructing roads traversing steep slopes involved some effort but was probably more efficient when transporting heavy goods. On the other hand, slopes tend to be gentler in the western third of the study area, while most Eisenstraße road sections are located in the eastern part. The correlation between the mean slope of Nicke road sections and M4 performance is not significant (correlation 0.04), with a probability of 82% that the variables are uncorrelated.[59]

In Table 11.2, the "Confirmed %" attribute was computed to analyse whether road sections documented on detailed maps created before 1800 or in Viabundus are more likely to be successfully replicated by the M4 cost model than road sections lacking this additional evidence (Figure 11.6). The reasons for creating the old maps vary, and consequently the reliability and accuracy of the depicted roads vary as well. But in most areas, the estimated error of the routes digitised from these old, detailed maps is less than 200 metres. Therefore, a 200-metre radius buffer was created for these digitised routes and the Viabundus roads. For each Nicke road section considered, the total length of stretches within this joint buffer was computed, and the percentage of this value in relation to the length of the road section was recorded in the "Confirmed %" column of Table 11.2. This variable exhibits a correlation with the M4-LCP performance (0.39). The "Confirmed %" and "Detour factor" variables have a correla-

57 *Nakoinz*, Parameter (2012), 78, introduced a similar concept for identifying the most plausible routes within a least-cost triangulation network.
58 An alternative feature is the average elevation range per kilometre, but the correlation coefficient for this variable with M4-LCP performance (0.27) is lower than that of the elevation range variable.
59 According to the PAST manual (see *Hammer*, Past 4 [2023]), the probability was computed using a two-tailed t-test, which is discussed for instance by *Shennan*, Quantifying ([2]1997) on 83–92.

tion of -0.57, suggesting that the Nicke road sections documented in historical sources are likely to follow a fairly direct path.

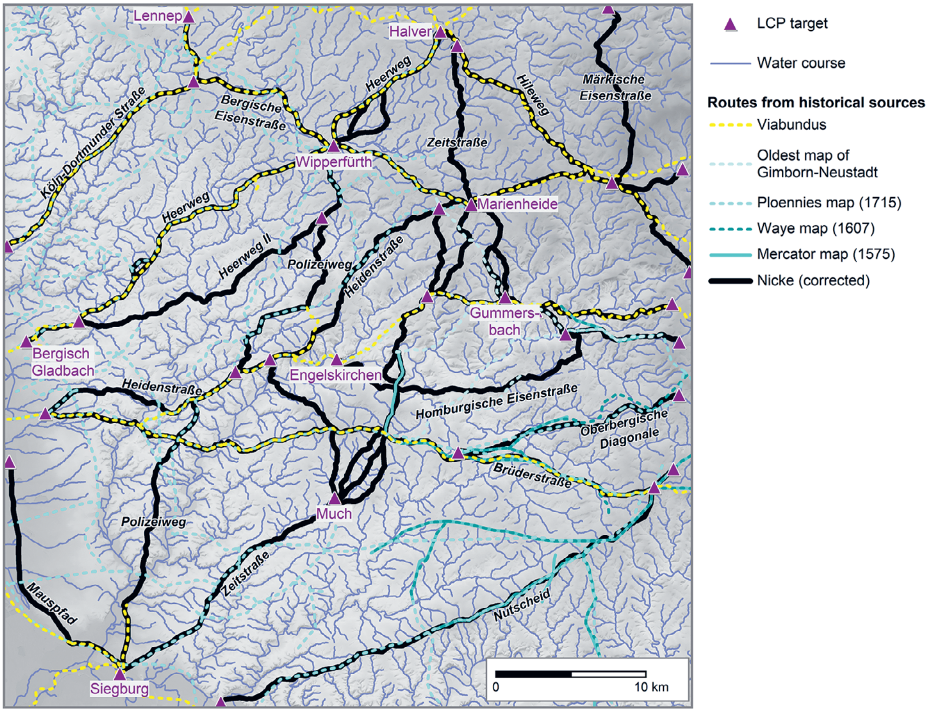

Figure 11.6: Comparing Nicke roads to roads digitised from old maps and provided by Viabundus.

The analysis revealed three variables that are correlated with M4-LCP performance: “Detour factor” (correlation: –0.37, p[uncorrelated]: 5.3%), “Elevation range (m)” (correlation: 0.36, p[uncorrelated]: 6.1%), and “Confirmed (%)” (correlation: 0.39, p[uncorrelated]: 4.2%).[60] The coefficient of determination can be used to estimate the ‘percentage level of explanation’.[61] For the three variables weakly correlated with M4-LCP performance, this value falls between 12.8% and 15.0%, indicating a modest level of explanation.

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60 Here, p[uncorrelated] indicates the probability that the considered variable and M4-LCP performance are not correlated. In statistics, the convention is to select a significance level of 5%, i.e. to reject the hypothesis that the two variables considered are correlated if p[uncorrelated] is less than 5% (e.g. *Shennan*, Quantifying [²1997], 56–57). At the 5% level of significance, the hypotheses regarding the correlation of the detour factor and elevation range with the M4-performance are rejected.
61 E.g. *Conolly/Lake*, GIS (2006), 151; *Shennan*, Quantifying (²1997), 143–144. This coefficient is the square of the Pearson correlation coefficient, multiplied by one hundred.

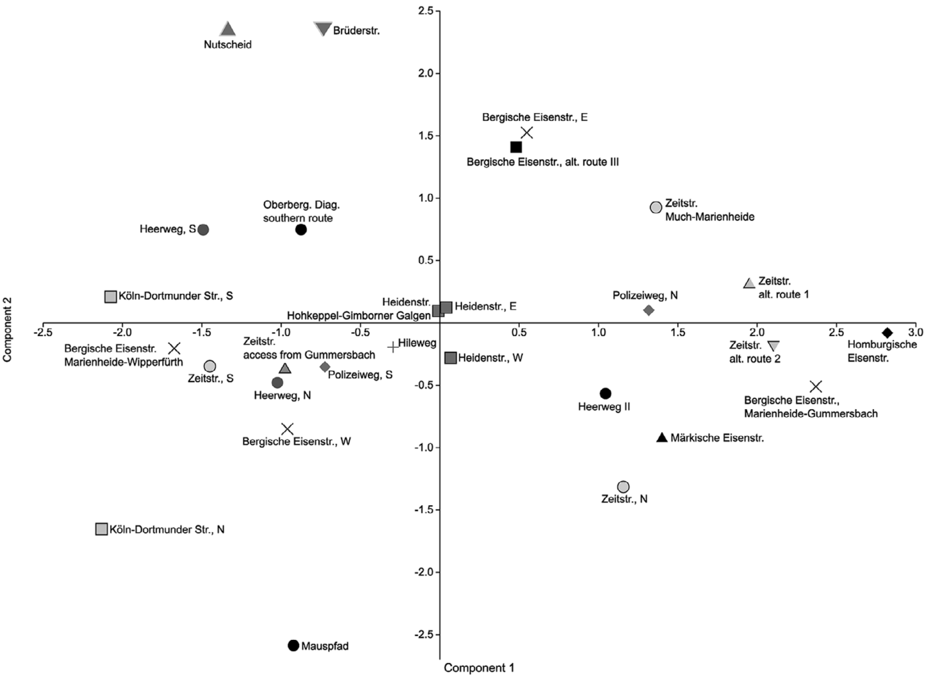

Figure 11.7: The first two components of the PCA result for characteristics of the Nicke road sections.

A principal components analysis (PCA),[62] utilising the standardised columns "Detour factor," "Elevation range," "Mean slope," and "Confirmed (%)" of Table 11.2 was conducted to identify groups of Nicke road sections with similar characteristics. The scatterplot of the first two PCA components accounts for approximately 76% of the variance in the considered characteristics. In Figure 11.7, the symbols representing the Nutscheid and Brüderstraße road sections are displayed side by side (both of which are partially depicted in Mercator's map). The Mauspfad road section stands out as an outlier. It is expected that symbols representing a road subdivided into several sections would be closely grouped together in the scatterplot, as observed in the case of the three sections of the Heidenstraße. However, the sections of the Bergische Eisenstraße and Zeitstraße exhibit a broader range of characteristics. Surprisingly, the characteristics of the road sections known as "iron transport routes" show significant variation.

62 *Shennan*, Quantifying (^{2}1997), 269–300.

11.5 A close look at some of the results

The analysis of the LCP characteristics does not fully explain the varying LCP performance. This section gives some examples of unsatisfactory LCP performance and discusses the reasons for this. The Mauspfad road in the southwest of the study area has the lowest M4 performance (13.7%) of all the road sections considered. This is likely due to the fact that this road is substantially different from the others, being located on the fluvial terrace of the Rhine and appearing to gravitate towards the edge of this terrace.

The M4 performance for reconstructing the Homburgische Eisenstraße is second lowest (13.8%). Two stretches of this road connecting Engelskirchen in the west with Derschlag in the east run through river valleys. It is evident that the cost model, with its high penalties for movement near rivers, cannot accurately represent this road. Instead, the M1-LCP closely aligns with an alternative road depicted on the oldest map of Gimborn-Neustadt (Figure 11.6). The detour to the Steinagger valley might be explained by the label "Pochwerk" (Figure 11.5), indicating a mill machine used for crushing materials by pounding, depicted on a map created between 1817 and 1828. The Homburgische Eisenstraße likely served to transport raw materials to this site and distribute the products.

Another road section with a very low M4 performance of 15.7% is the western part of the Bergische Eisenstraße between Bergisch Born and Wipperfürth. However, three other sections of this Nicke road are quite successfully replicated by LCPs based on the M4 cost model (Table 11.2). The SDH study demonstrated that inserting a waypoint in the town of Hückeswagen[63] significantly improves performance. Several of the SDH-LCPs (with the destination Lennep instead of Bergisch Born)[64] suggest an alternative route. They roughly coincide with the Nicke and the Viabundus roads west of Wipperfürth. These LCPs cross the Wupper close to the remains of a motte-and-bailey castle clearly visible in ALS data, with a sunken lane about 200 metres northeast of the fortification (Figure 11.8). Some sections of the SDH-LCPs coincide with roads depicted on the "Uraufnahme". The ALS data visualisation in Figure 11.8 also highlights landscape changes, mainly due to modern construction activities, which likely impacted the LCP generation. Berges's description[65] of the Bergische Eisenstraße differs from that of Nicke and the Viabundus road. Berges suggests that the old road coincides with the Ploennies road, which departs from the centre of Hückeswagen in a westerly direction and turns northwest near Waag (Figure 11.8). Bundles of sunken lanes on both slopes of the Dörpe valley between Forsten and Brasshagen provide evidence of a former road

63 According to *Pampus*, Erstnennungen (1998), 146, the place name Hückeswagen was first mentioned in 1085.
64 Bergisch Born was chosen in the present study to avoid an overlapping road section with the Köln-Dortmunder Straße.
65 *Berges*, Eisenstraße (1993), 30.

approximately 1 kilometre north of the Bergische Eisenstraße route described by Nicke and mapped by Viabundus. Both the sunken lane sites and the style of the depiction of the road between Hückeswagen and Bergisch Born – on a map created between 1817 and 1828 – support the conclusion that Nicke's description of the road is likely inaccurate. The LCP labelled Q17-25-2-1.8-1.7 in Figure 11.8 (also shown in Figure 11.5) effectively replicates the Ploennies road northwest of Waag.

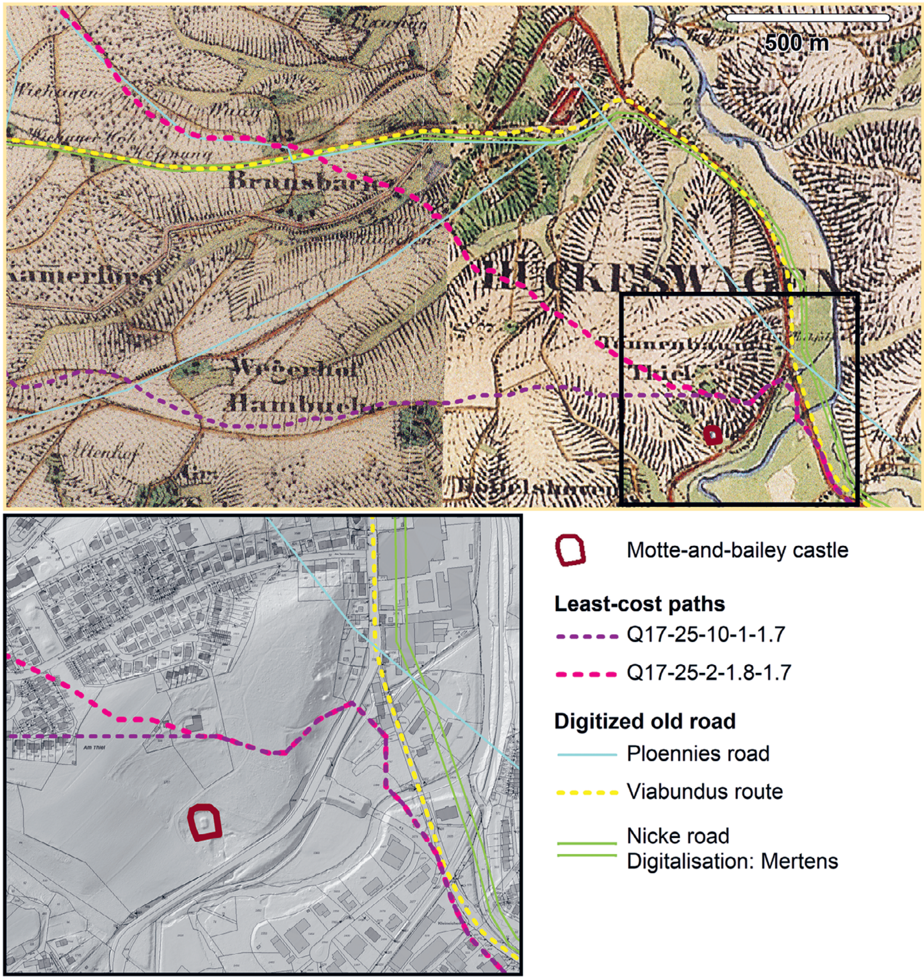

Figure 11.8: Bergische Eisenstraße near Hückeswagen. The Least-Cost Paths (LCPs) suggest a road near a motte-and-bailey castle. Background maps, top: "Uraufnahme" created in the 1840s, bottom: ALS data overlaid with a modern cadastral map.

Berges also describes a branch of the Bergische Eisenstraße that diverges from the route connecting Wipperfürth and Marienheide at Sattlershöhe and proceeds to Gummersbach, bypassing the detour through the town centre of Marienheide.[66] Nicke does not mention this road, although it is corroborated by several SDH-LCPs between Wipperfürth and Gummersbach.

The northern segment of the Zeitstraße also exhibits a low M4-performance (23.6%). In this case, introducing penalties for moving through wet areas resulted in a significant drop in performance (M3: 71.2%). The primary reason for this decline is an issue with the wet area layer at the location of the dam known as Lingesetalsperre (marked in Figure 11.5). Penalties for crossing wet areas are not included in the isotropic cost layer for the reconstructed watercourse section within the dam, even though wet areas surround the Lingese watercourse. As a result, the M4-LCP selects a low-cost route through the dam, approximately 1 kilometre east of the correct crossing point over the Lingese, as replicated by the M3-LCP. Another example of a significant performance drop (M3: 90.9%, M4: 36.2%) is the Nicke road "Zeitstraße, access from Gummersbach". Evidently, the wet area zones avoided by the M4-LCP may have been relatively safe to traverse. The Nicke road section of the Zeitstraße connecting Much with Marienheide remains close to two watercourses for several kilometres. Hence, it is not surprising that the M2-LCP outperforms the M3- and M4-LCPs.

With an M4 performance of 54.2%, the Brüderstraße is relatively well-replicated over certain stretches. As previously mentioned, the western part of the study area differs from the hilly eastern section, possibly accounting for the deviations in LCPs from the Nicke road in the western part. The fact that watercourses are intersected by the Brüderstraße but avoided by the M4-LCP appears to be the primary reason for the deviations of the Nicke road from the M4-LCP.[67]

11.6 Discussion and conclusions

Obtaining reliable data for mapping the medieval road network in any part of Germany is daunting. The earliest relevant pre-industrial maps showing roads are of limited accuracy and do not encompass the entire study area. In this scenario, Nicke's books provide a solid foundation for investigating historical mobility patterns in the study area. Nevertheless, certain sections of the old roads are ambiguously described by Nicke, leading to uncertainty about digitising them. Moreover, Nicke's accounts may not always be accurate. For instance, evidence suggests that the westernmost part of the Bergische Eisenstraße deviates from Nicke's description. Unfortunately, dating the Nicke

66 *Berges*, Eisenstraße (1993), 32–33.

67 *Nicke,* Brüderstraße (2000), discusses on 48–52 the locations where the Brüderstraße crosses watercourses, but omits four creeks in the study area, i.e., Holzer Bach, Dresbach, Katzbach, and Bierenbacher Bach, all of which are depicted on the "Uraufnahme" map. The M4-LCP avoids crossing the Holzer Bach, the Katzbach, and the Bierenbacher Bach.

roads is challenging due to a lack of archaeological investigations and artefacts. Consequently, the Nicke roads might not have existed concurrently. A multivariate approach was presented investigating whether roads created in a particular era or primarily used for a specific purpose exhibit similar route characteristics. The PCA based on four Nicke road characteristics reveals similarities (e.g. Heidenstraße) as well as significant dissimilarities (e.g. Bergische Eisenstraße, Zeitstraße) between different segments of the same road. Some of the Nicke road sections were part of several roads, which may account for some of the disparities. This is an issue that warrants further investigation.

Various archaeologists have employed LCP approaches to reconstruct the roads connecting two or more roughly contemporary sites.[68] Some of these studies give the impression that a single method for computing LCPs is suitable for general human mobility, irrespective of factors like soil, land use, climate, historical period, load, and means of transportation. This article showed that a wide range of cost models is available and that it is difficult to identify the most appropriate model. Issues with popular LCP algorithms were discussed that can result in significant deviations from the true optimal path. The LCP algorithm presented in this article should be refined in the future to avoid generating routes along the contour lines of steep slopes because such roads require construction work.[69] The discussion of problematic LCP results suggests adjustments to the isotropic cost grid concerning watercourses less than 3 metres wide. Although ALS data indicate that modern creeks are carved into the terrain, traversing some of them may not have been particularly challenging. This is another issue that warrants further investigation.

Many archaeological LCP studies aim to reconstruct the road network of a specific period by connecting important known sites using LCPs.[70] However, many old maps depict important settlements at some distance from the main roads of the time. For instance, only two out of seventeen church settlements on Mercator's map were crossed by the main roads depicted on the map.[71] The castle of the rulers of the Homburg territory was also at some distance from the roads. Therefore, identifying appropriate targets and waypoints for LCP generation poses a non-trivial challenge.

The LCP study presented here does not consider water travel, which may have been possible on some of the rivers in the study area. Yet, none of the publications describing the region's medieval and early modern economy mention water-based transport. Due to various factors, including currents, weather conditions, and different types of vessels, modelling water travel is at least as complex as finding an adequate cost model for land transport.[72]

68 For references, see *Herzog*, Spatial analysis (2020).
69 *Nicke*, Wege (2001), 13.
70 E.g. *Barbe*, Fernwege (2007).
71 Mercator, Grundtliche Beschreibungh. Ed. *Weirich*.
72 Some references with respect to past water travel are given by *Verhagen/Nuninger/Groenhuijzen*, Pathways (2019), 28.

Several authors discuss socio-cultural costs, such as visibility or safety. In the study area, roads on ridges offer expansive views and enhanced security compared to valley routes, particularly in areas lacking dense forest cover. Potential adversaries would need to scale a slope before reaching a road on the ridge, making any attack more challenging. For these reasons, the attraction of ridges could be modelled as a socio-cultural cost, similar to Barbe's approach.[73] In the study area, the M4-LCPs often align with ridges, thus this modification of the cost model seems unnecessary. Appropriate penalties for crossing creeks appear to be the primary concern.

In the absence of historical or archaeological evidence, reconstructions of early medieval major trade routes are highly hypothetical. The reasons for this are the wide variability of cost models and the fact that not even all settlements with a church were integrated in the early modern main road network. However, where historical evidence of an early modern road is available and may be traced back to earlier times, the LCP approach can be used to identify road sections unlikely to have changed, i.e. those road sections depicted on historical maps aligning with several LCPs based on different cost models. This may be supplemented by an analysis of the uncertainty of the LCPs[74], with the aim of identifying road sections where any significant deviation from the initial LCP incurs a substantial amount of costs. Referring to the present study, the Nutscheid road and large parts of the Brüderstraße were most probably in use already in the early Middle Ages.

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73 *Barbe*, Fernwege (2007), 49.

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