Process-Explicit Model Reveals Structure of Roman Roads in the Roman Empire

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Summary

Roadways constructed by past societies are routinely characterised by a single defining feature, their straightness[1–4]. At the same time, the position of roadways within the landscape was variable, influenced by the topographic constraints and economics of transport[4–6]. Yet our understanding of this variability is limited, despite roadways providing the foundation for inferring the structure and objectives of a past society[7–9,6,10,11]. Here we show that roadways in the Roman empire did not conform to a single, unifying principle of straightness but were instead flexible to topographic constraints. We found that the majority of roadways in the Roman empire were traversable by those on foot and when using a wheeled vehicle. Our results demonstrate that Roman roadways were preferentially positioned within the landscape to minimise steep slope gradients which would have posed difficulties for traversal. We anticipate that the approach presented here to be a starting point that overcomes the scarcity of direct evidence for past decision-making when choosing where to position roadways within the landscape[3,4,12]. This holistic, comparative approach allows for the interplay of topographic constraints and economies of transport on the position of roadways to be quantified, with the socio-economic and objectives of past societies better understood.

Main

Roadways constructed by past societies are routinely characterised by a single defining feature, their straightness[1–4]. The Mayan *Cobá–Yaxuná Sacbe* ('white road'), the inland route of the *Inka* Qhapaq Ñan ('Royal road'), and the Roman *Via Appia* of the Roman empire crossed mountains, valleys, and marshlands with little deviation. At the same time, the position of past roadways was flexible, influenced by both topographic constraints such as mountain passes, ravines, and steep gradients; and economics of transport, including the types of goods being transported[4–6]. Yet our understanding of this variability across past roadway systems is limited. This is despite roadways providing a robust empirical foundation for inferring the socio-political and economic structure and objectives of past societies[7–9,6,10,11], overcoming the scarcity of direct evidence for past decision-making[3,4,12]. A major obstacle is the classification of roadways into typologies based on their construction, proposed function, and the sites that they connect[3,6,10,13–17]. The usefulness of such typologies for understanding variability in archaeological material including roadways is a subject of long debate[7,6,10,17–22].

Here, I use a process-explicit, hierarchical movement model to estimate the variability in the influence of topographic constraints on the position of Roman roadways in Roman Wales and across the Roman empire. Detailed knowledge on the position of multiple road sections[23], combined with the mountainous terrain of Wales, make the study of roadways within this region of the Roman empire highly suitable. Roadways in Wales also have two additional advantageous that promote transferability to roadways across the Roman empire: 1) Roman roadways in Wales are thought to have been constructed *de novo*, limiting the impact of pre-existing roadways influencing their position within the landscape; and 2) like other regions of the Roman empire, roadways were constructed or overseen by the Roman army[23]. A larger-scale analysis of roadways across the Roman empire, or other past societies, is prohibited by the often dubious provenance of many reported roadways and the lack of systematic standards when recording their position within the landscape[24,25].

Results

Results reveal substantial variability in the influence of topographic constraints on the position of the 62 known Roman roadways in Wales (**Fig. 1**). Median posterior estimates for the rate of incline from the minimum influence of topographic constraints across individual roadways (parameter b) ranges between 0.25 and 35.69. The majority of these roadways (74%, 46 out of 62) are more influenced by topographic constraints than expected when minimising time while hiking (Tobler's Hiking Function, parameter b = 3.5)[26]. Roman roadways also possess shallower slope gradients at a rate higher than expected while hiking (**Extended Data Fig. 1**). Median posterior estimate ($\bar{b}$) for roadways across the Roman empire is 6.31 [0.27-35.60, 95% Credible Interval] with a standard deviation (σ) of 0.76 [0.03-3.86]. Like the majority of roadways in Wales, the influence of topographic constraints on roadways across the Roman empire is also greater than expected while hiking.

Maximum slope gradient for individual roadways ranges between 0.03 and 0.44. 55 roadways (88.7%) in Wales are shallower than the maximum slope gradient of 0.25 for roadways in Roman Scotland, a similarly mountainous region of the Roman empire[27]. 47 roadways (75.8%) also possess maximum slope gradients shallower than 0.20, or that which is deemed too steep to have been traversable by a wheeled vehicle without assistance[5]. In contrast, only 29 (46.8%) roadways have a maximum slope gradient shallower than the preferred maximum slope gradient of 0.125 for Roman roadways in Britain[28].

56 roadways (90.3%) have a maximum slope gradient shallower than the 0.29 critical slope gradient—that is, the maximum slope gradient at which an individual can efficiently ascend or descend without slipping or experiencing significant difficulty—while hiking, navigating wooded environments, or participating in hill running races[26,29–33]. 36 roadways (58.1%) also have a maximum slope gradient shallower than the 0.15 critical slope gradient for a fully loaded Roman wheeled vehicle[34]. 13 roadways (20.97%) are also shallower than the 0.08 critical slope gradient estimated for Roman roadways in south-west England[35].

For roadways across the Roman empire, the majority (68.63%) are estimated to have a critical slope gradient below that while hiking. Meanwhile, only 46.95% of roadways have critical slope gradients below the 0.15 critical slope gradient for wheeled vehicles (**Extended Data Fig. 2**).

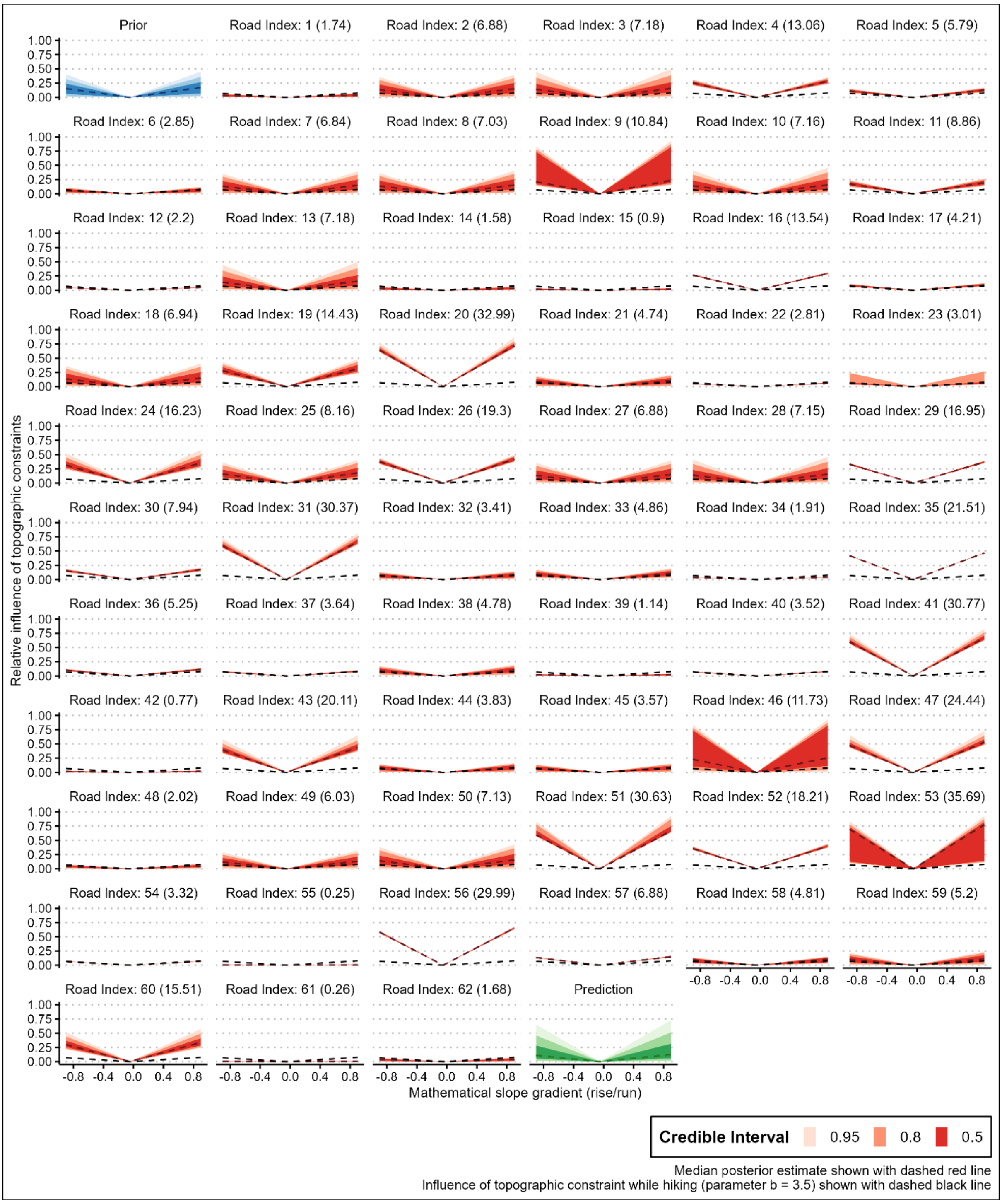


Fig. 1. Estimated relative influence of topographic constraints on the position of Roman roadways. 250 prior estimates drawn from the prior distribution (top left, blue), 250 accepted parameter values for each roadway (red), and 250 predicted estimates drawn from posterior distributions for Roman roadways across the Roman empire (bottom right, green). Median posterior estimates for the rate of incline from the minimum influence of topographic constraints (parameter *b*) shown in brackets

Discussion

The first conclusion we can draw from the results is that the influence of topographic constraints varied across Roman roadways in Wales. Roadways did not conform to a single, unifying principle of straightness but were flexible to the influence of topographic constraints.

The results show that the majority of roadways in Wales were shallow enough for both traversal when on foot and using a wheeled vehicle. Roman roadways traversable by foot and wheeled vehicles facilitated the movement of armies and their supplies, essential for the conquest and consolidation of the region[23]. Roadways in Wales were however steeper than roadways in Britain, reflecting the more mountainous terrain of Wales and its greater influence on the position of roadways. The influence of the terrain on the steepness of roadways is further corroborated by Roman roadways in Scotland also being steeper than roadways in Britain. Nonetheless, the position of roadways in Wales is shown to have been preferentially chosen to minimise the frequency of steep slope gradients, reducing the difficulty of traversal compared to when hiking off-road. The desire to minimise the frequency of steep slope gradients, or 'lost descent', along Roman roadways has been noted previously in Roman Cyprus, also a mountainous region of the Roman empire[25].

The majority of roadways across the Roman empire are also estimated to have been more influenced by topographic constraints than while hiking. Like Wales, roadways across the Roman empire would have been less difficult to traverse than when hiking off-road. Nearly half of roadways are however estimated to have presented difficulties when using a wheeled vehicle. A number of approaches are however known to have been used to ease this difficulty, including the use of steps[5]. The presence of wheel ruts on steps[36] for example indicates that steep roadways, while presenting greater difficulty, were still traversed by those using wheeled vehicles. Likewise in Roman Judea, roadways constructed for transporting economic goods such as salt, asphalt, and sugar were structurally modified to minimise their slope gradient and reduce difficulty when using a wheeled vehicle[37].

Roman roadways across the Roman empire were pivotal for its initial expansion, consolidation, and political and socio-economic integration. Roadways shallow enough to accommodate wheeled vehicles facilitated the political integration of elites during the rise of Rome[38,39]. Throughout the Roman empire, roadways also influenced the founding of new towns and cities, amplified the flow of goods, materials and people, and integrated local communities into the wider Roman economy[40]. It is thus imperative that variability in the influence of topographic constraints on the position of Roman roadways is integrated within studies of the Roman world.

At its most fundamental, the hierarchical movement model presented here overcomes the scarcity of direct evidence for past decision-making and reveals variability in how past roadways were positioned within the landscape. The model is also agnostic to typologies, offering an alternative framework for understanding 1) how the position of past roadways was influenced by topographic constraints within an individual society and 2) whether and how this influence differed across past societies around the world. Through this holistic, comparative approach, the interplay of topographic constraints and economies of transport on the position of roadways can be quantified, with the socio-economic and objectives of past societies better understood.

Materials and Methods

Roman roadways in Wales

The position of 62 known Roman roadways in Wales (**Extended Data Fig. 3**) were digitised from '*Roman frontiers in Wales and the Marches*'[23]. The position of individual roadways included within this analysis are those that show extant earthworks such as quarry pits or the agger (the embankment of the roadway); or well-recorded buried features[23]. Roadways whose evidence was less substantive, or those that were conjectured were not included within the analysis.

Hierarchical Movement Model

The influence of topographic constraints on the position of 62 Roman roadways was estimated using a Bayesian hierarchical movement model. This influence was modelled as the reciprocal of an exponential function defined as follows

$$TC_i \sim \frac{1}{\exp\left(-b_i * abs(x + 0.05)\right.}$$

$$b_i \sim TruncNorm(\bar{b}, \sigma)$$

$$\bar{b} \sim TruncNorm(1, 10)$$

$$\sigma \sim Exponential(1)$$

where TC_i is the influence of topographic constraints on the position of individual Roman roadway i in Roman Wales across mathematical slope gradients (x), b_i is the rate of incline from the minimum influence of topographic constraints, $\bar{b}$ is the rate of incline from the minimum influence of topographic constraints on the position of Roman roadways across the Roman empire, and σ is the standard deviation for the rate of incline from the minimum influence of topographic constraints on the position of Roman roadways across the Roman empire.

Priors are weakly informative and informed by realistic ranges. For example, restricting b_i to positive-only values ensures that the influence of topographic constraints on the position of roadways cannot decrease with increasing slope gradient. To establish the robustness of the hierarchical movement model, a dataset of comparable sample size (n = 62) was simulated. The model was able to correctly estimate the majority of parameters within the 95% credible interval (**Extended Data Fig. 4**).

Least-cost path calculation

250,000 b_i parameter values drawn from $\bar{b}$ and σ were used to calculate 250,000 TC_i. Each TC_i was used to calculate 250,000 least-cost paths for each Roman roadway (in total, 15,500,000 least-cost paths). Least-cost paths represent the optimal path between two locations using a raster surface that quantifies the cost of traversing from one cell to another[41]. The topography of Wales was represented by the Ordnance Survey 50 metre Digital Elevation Model[42]. Least-cost paths were calculated using the *leastcostpath* R package[43].

Parameter inference

b_i, $\bar{b}$, and σ parameter values for each of the 62 Roman roadways were estimated using Approximate Bayesian Computation[44]. Posterior distributions were estimated by accepting 250 (0.1%) parameter values with the lowest Path Deviation Index value[45]. The Path Deviation Index quantifies the deviation between each least-cost path and its associated Roman roadway. Path deviation index is defined as follows

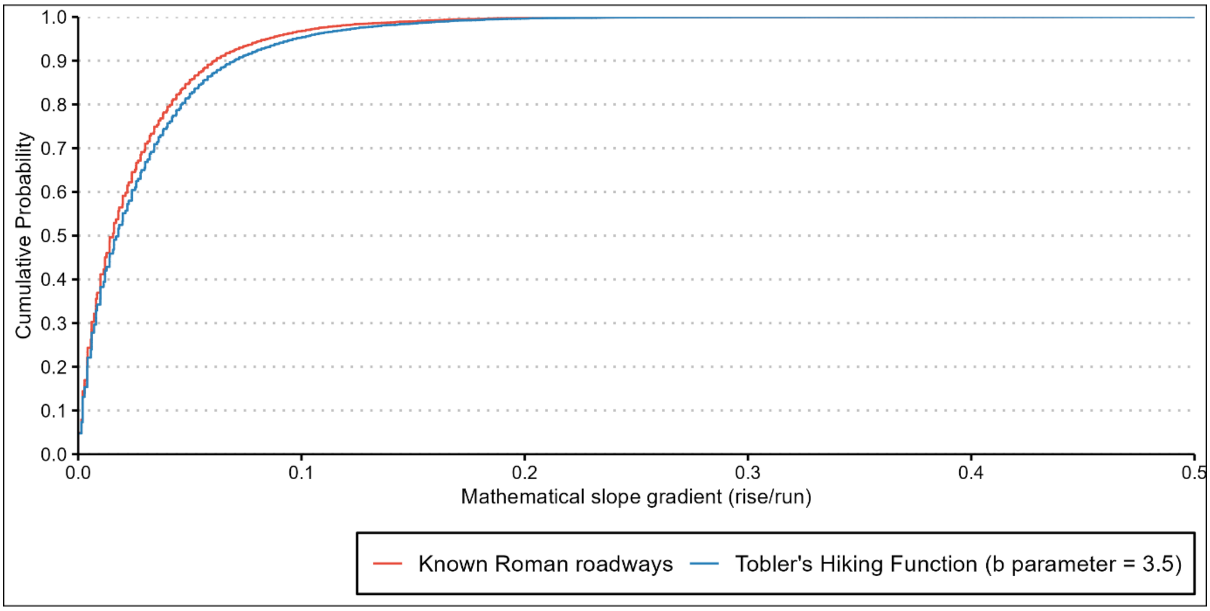
$$path\ deviation\ index = \frac{area\ between\ two\ paths}{Elucidean\ idstance\ of\ the\ shortest\ path}$$

Mathematical slope gradient calculation

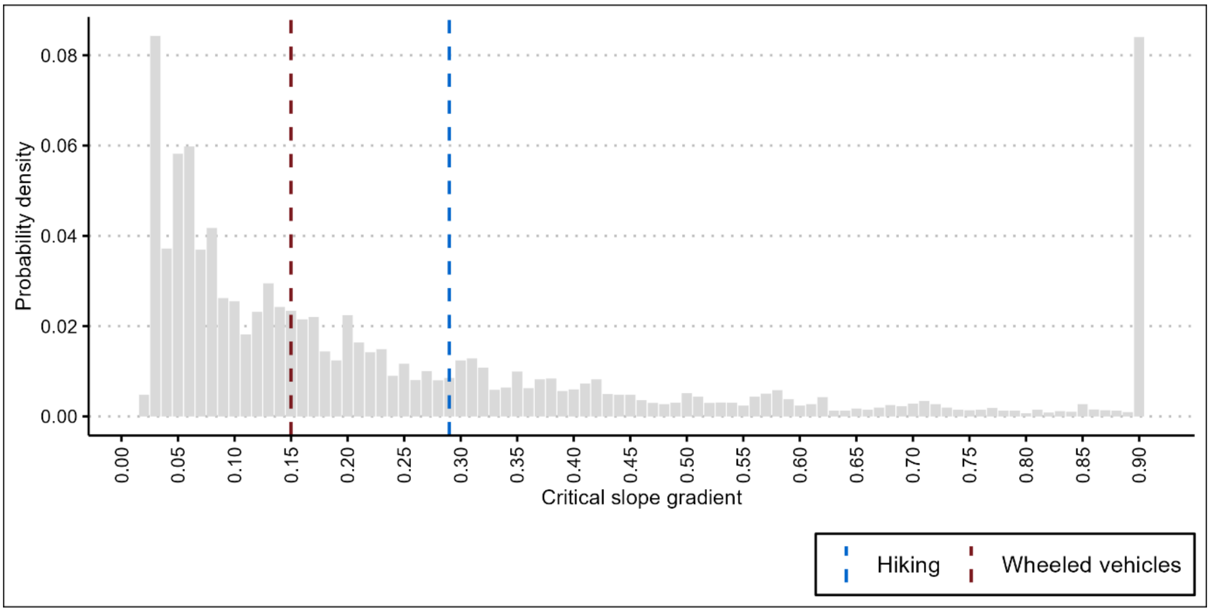
The mathematical slope gradients of each Roman roadway were calculated as the difference in elevation between two neighbouring cells that are crossed by the roadway. Maximum slope gradient refers to the maximum slope gradient calculated for each Roman roadway. While the calculation of slope gradient is sensitive to the resolution of the Digital Elevation Model, reported slope gradients can be interpreted as being the lower-bound. That is, decreasing the resolution of the Digital Elevation Model also decreases the calculated mathematical slope gradients (**Extended Data Fig. 5**). Therefore, using a Digital Elevation Model with a coarser resolution will result in shallower reported slope gradients. As a corollary, it is expected that using a Digital Elevation Model with a finer resolution will result in steep slope gradients.

The critical slope gradient of each Roman roadway was calculated as the mathematical slope gradient (-0.9 to 0.9 with intervals of 0.01) at which vertical speed (uphill or downhill) is maximised.

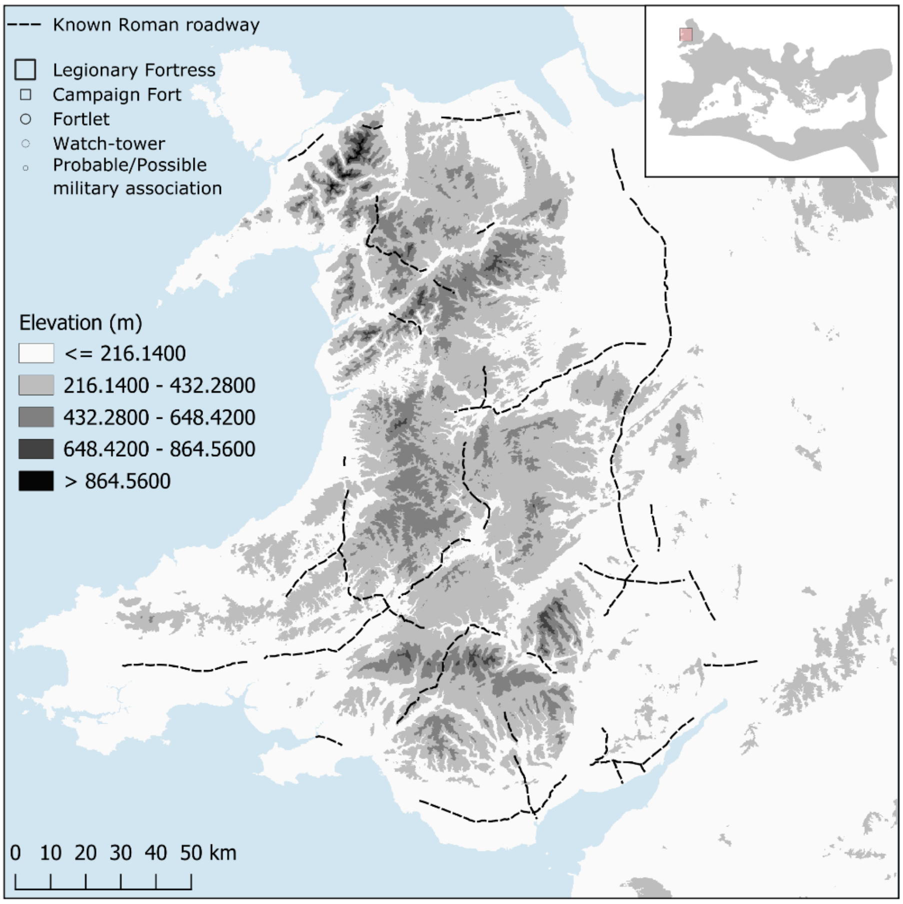
Extended Data Figures



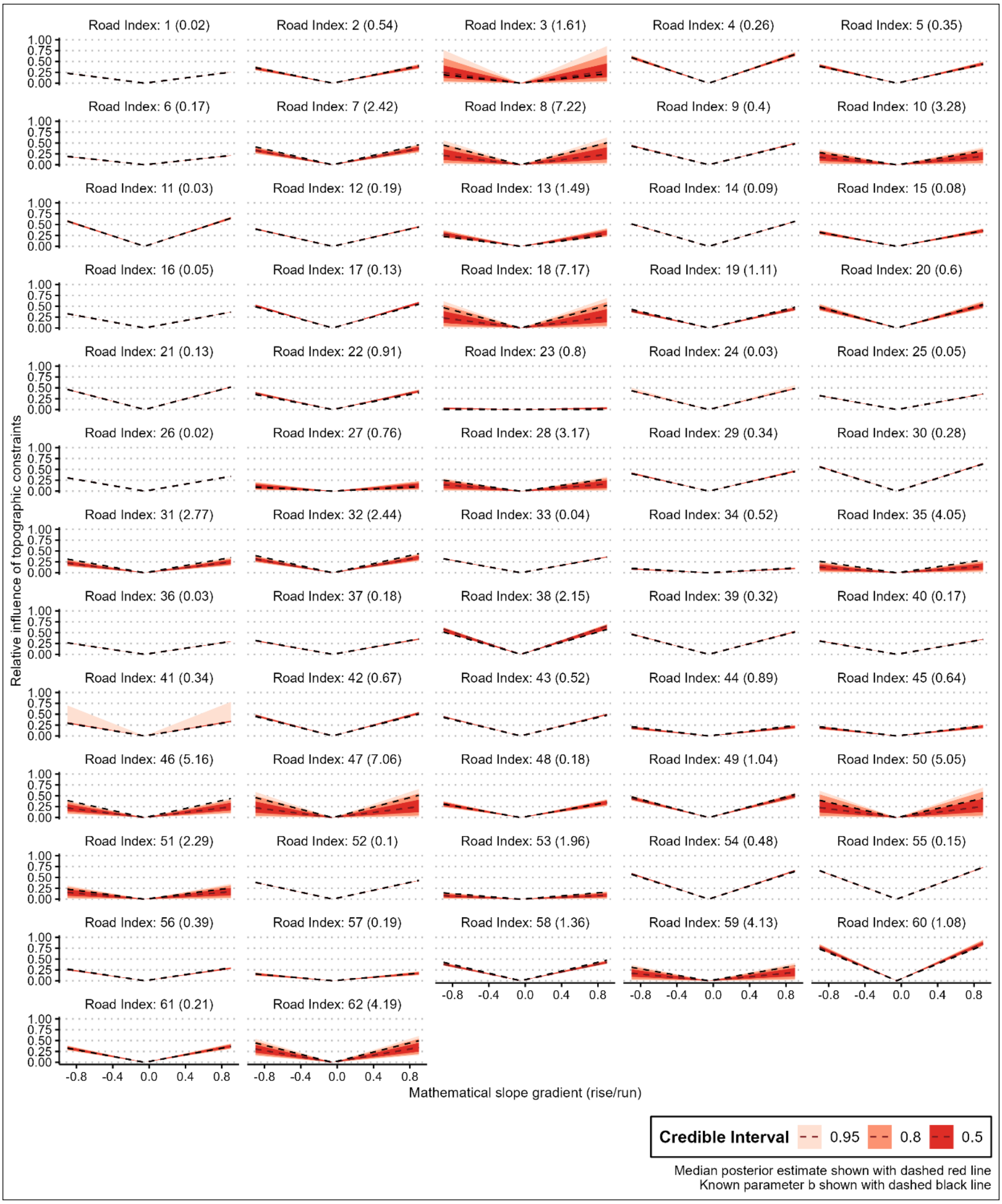
Extended Data Fig.1. Mathematical slope gradients cumulative probability for Roman roadways in Wales and predicted routes while hiking. Mathematical slope gradients for known Roman roadways calculated using the median posterior estimates for the rate of incline from the minimum influence of topographic constraints (parameter b) for each roadway. Mathematical slope gradients when hiking calculated using a fixed parameter b value of 3.5



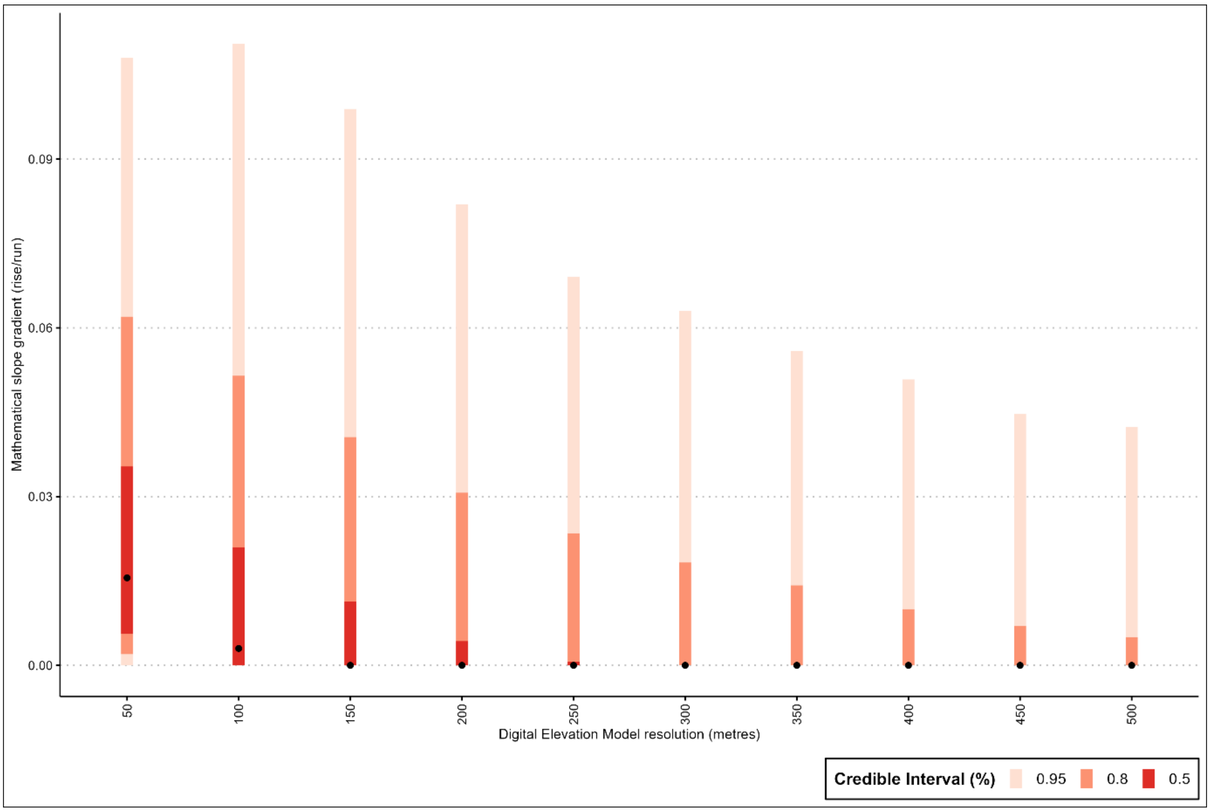
Extended Data Fig.2. Critical slope gradient for Roman roadways across the Roman Empire. Critical slope gradient while hiking (0.29) and when using a wheeled vehicle (0.15) shown with dashed blue and red lines, respectively. Critical slope gradient refers to the maximum slope gradient at which an individual can efficiently ascend or descend without slipping or experiencing significant difficulty. Critical slope gradients for Roman roadways across the Roman empire estimated using the mean parameter b value drawn from 1,000 $\overline{b}$ and σ values for each accepted $\overline{b}$ and σ value



Extended Data Fig.3. Map of study area. Known Roman roadways (n = 62) used in the analysis



Extended Data Fig.4. Estimated relative influence of topographic constraints on the position of simulated routes. 250 accepted parameter values for each roadway (red). Absolute deviation between median posterior estimates for the rate of incline from the minimum influence of topographic constraints (parameter b) and the known parameter shown in brackets



Extended Data Fig.5. Mathematical slope gradients for Roman roadways in Wales. Mathematical slope gradients for Roman roadways decreases with decreasing resolution of Digital Elevation Model. Mathematical slope gradients for known Roman roadways calculated using the median posterior estimates for the rate of incline from the minimum influence of topographic constraints (parameter b) for each roadway

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