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Generative inference model reveals political and economic motivations for road construction in past societies

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Abstract

The construction of roads in past societies reflects a trade-off between a preference for straightness and the influence of slope gradient. This trade-off is, however, also conditioned by other factors, principally the political and economic motivations of a past society. Our understanding of this trade-off and its relationship to these motivations is poor, hindered by qualitative studies that fail to explain variability in road construction, and non-comparative quantitative approaches. Here, we introduce a hierarchical, generative inference model that simulates roads using explicit decision rules to estimate the influence of slope gradient on 62 well-evidenced Roman roads in modern-day Wales. Our results reveal substantial variability, with Roman roads not conforming to a single unifying *straightness-gradient* trade-off. We relate this trade-off to political and economic motivations to provide a unified, comparative framework for inferring motivations for road construction, both within the Roman Empire and across past societies more broadly.

Introduction

Roads constructed by past societies are routinely characterised by a single defining feature, a preference for straightness (Margary, 1973, 18–22; Chevallier, 1976, 114–116; Nials, 1983, 6.1–6.50; Earle, 1991; Bekker-Nielsen, 2000; Shaw, 2008, 64–79). Roads were, however, also conditioned by slope gradient and its impact on transportation technology, principally the mechanical requirements of wheeled vehicles (Chevallier, 1976, 92–93). The position of roads in the landscape was thus a trade-off between straightness and slope gradient. Variability in this *straightness-gradient* trade-off provides a proxy for the underlying motivations for road construction in a past society. Earle (1991) and Trombold (1991) state that straighter roads reflect political motivations, given the required cost and labour mobilisation. The construction of the Roman *Via Appia* in Italy—famous for its straightness—is, for example, suggested to reflect the sponsors' need of patronage from elite families (Macbain, 1980) (Fig. 1).

Yet, descriptions of this trade-off and its relationship to motivations remain predominately often qualitative and vague. While previous studies have noted that straighter roads are easier to construct in less rugged terrain regardless of motivations (Earle, 1991; Hassig, 1991), qualitative frameworks struggle to distinguish between two explanatory scenarios: (1) when a road is straight *because* the terrain is less rugged and offers no topographic resistance; and (2) when a road is straight *despite* the more rugged terrain. A tendency to narrowly focus on individual roads located in rugged terrains (Verhagen and Jeneson, 2012; Fonte et al., 2017; Lewis, 2021; Lewis, 2024a), and the use of

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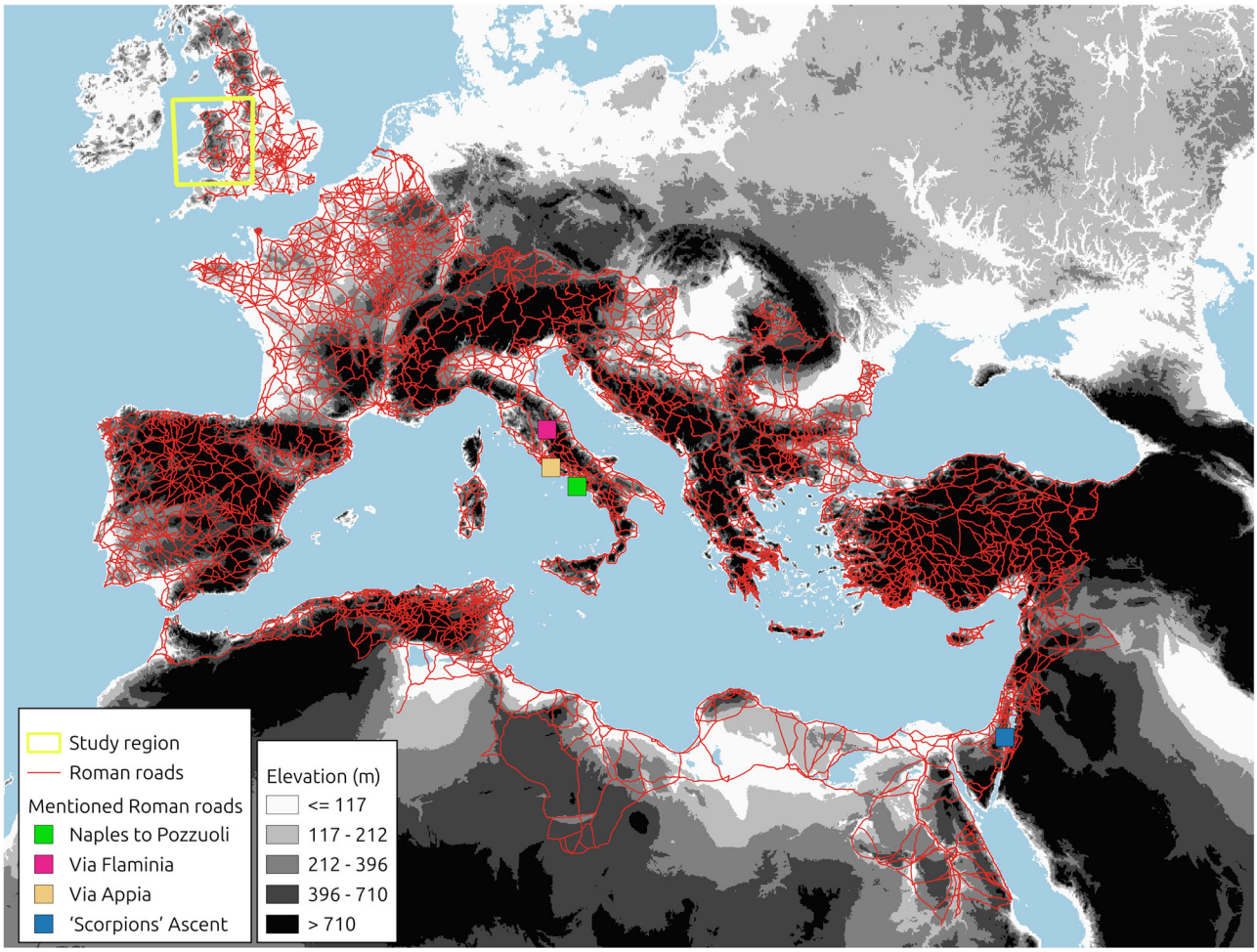


Fig. 1 Roman roads in the Roman Empire. Known, conjectured, and hypothesised Roman roads are shown with red lines and derived from De Soto et al. (2025) and Brughmans et al. (2024). Study region is shown by a yellow box. Location of named Roman roads mentioned in this study are shown by coloured squares. Projected coordinate reference system used here is the Global Mercator (*EPSG:3857*).

quantitative models that assume the influence of slope gradient on movement is uniform (Lewis, 2024a), further obscures variability in the *straightness-gradient* trade-off and, by extension, the inferred motivations for road construction. More generally, Earle (1991) suggests that the primary justification for road construction in states was political, with roads in chiefdoms also politically motivated but additionally used for ceremonial purposes. Hassig (1991) similarly suggests that road construction was primarily motivated by political and economic reasons, with the maintenance of religious and social ties secondary. Shaw (2008) also separates motivations for the construction of Mayan roads into political and economic: while Mayan roads could have simultaneously met multiple functions, including social, ritual, and symbolic, they primarily served to exert power, control, and ownership of territory.

Here, we introduce a simulation-based, hierarchical, generative inference model to estimate the influence of slope gradient on the position of roads constructed in the past (Lewis et al., 2026). This hierarchical framework facilitates the simultaneous estimation of individual road-level parameters and population-level trends by generating synthetic roads and identifying decision rules that best reproduce the position of observed roads. We relate the estimated influence of slope gradient to road straightness (*straightness-gradient* trade-off) and infer the political and economic motivations for road construction in past societies. As a demonstrable case study, we model multiple well-evidenced Roman roads in modern-day Wales recorded as part of a large-scale reappraisal of current evidence (Evans et al., 2010). The proposed hierarchical framework addresses the limitation of global models, such as Tobler's Hiking Function (Tobler, 1993), that assume a uniform relationship between slope gradient and movement cost (Lewis,

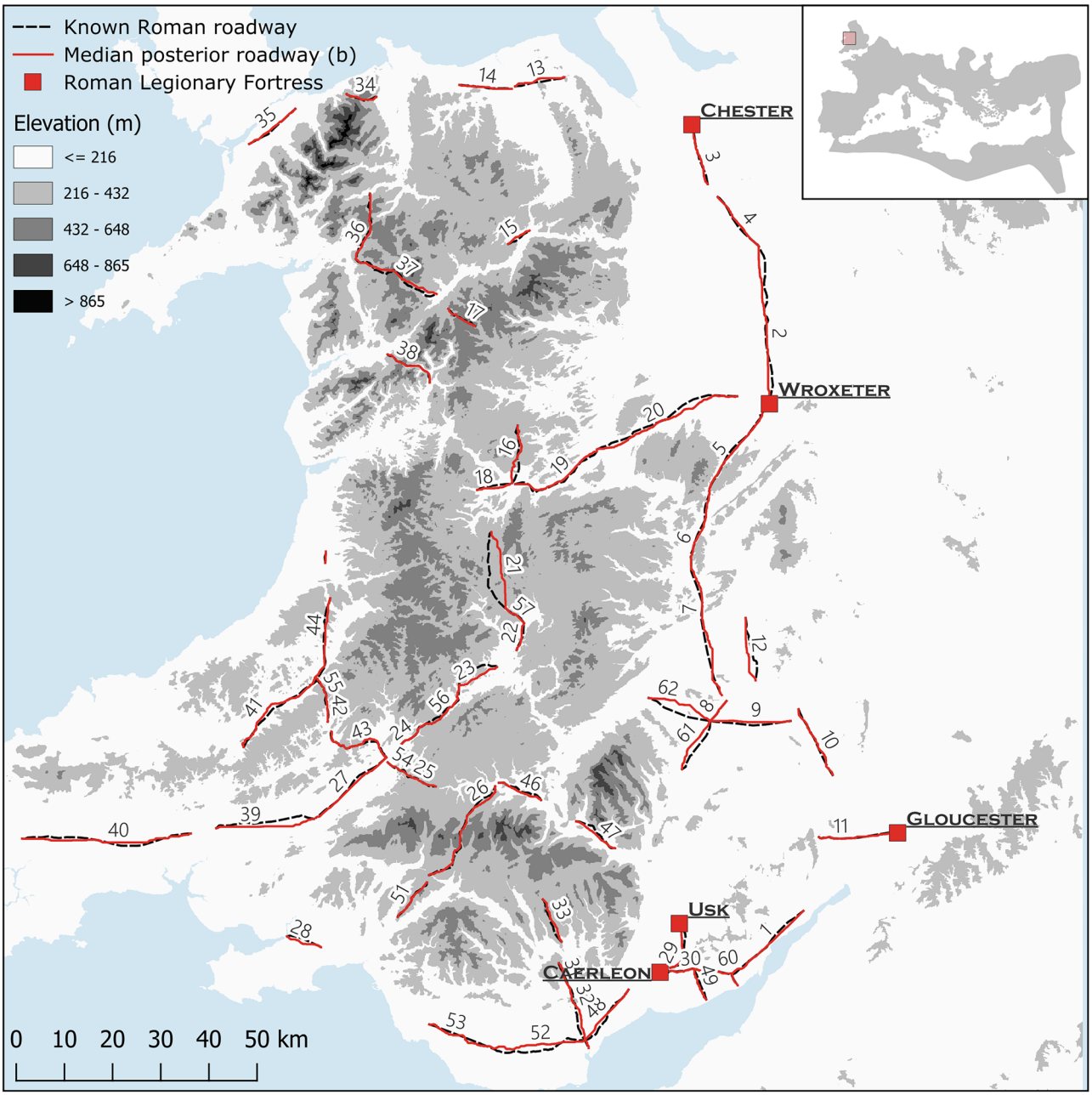


Fig. 2 Known and modelled Roman roads in Wales. Modelled Roman roads using median posterior estimates for the rate of decline from the maximum influence of slope gradient (parameter b) are shown with red lines. Known Roman roads are shown with dashed, black lines. Unique numbers alongside each modelled road correspond to index values in Fig. 3. The inset shows the AD 117 extent of the Roman Empire.

2024a). By employing partial pooling within the hierarchical model (Crema, 2025), the framework allows the influence of slope gradient to vary across individual Roman roads, thereby capturing localised topographic or engineering idiosyncrasies. While the model operates on the prior assumption that Roman roads share a common generative process, and are thus more similar to one another than unique, this hierarchical structure does not enforce uniformity. Instead, it uses the global distribution to inform, rather than dictate, road-specific parameters, balancing group-level trends with observed local variation. Detailed knowledge of the position of multiple road sections, its lack of formalised roads before the Roman conquest, combined with its flat coastal plains, hills, and mountains (Evans et al. 2010), makes Wales a highly suitable case study for examining variability in roads constructed in the Roman

Empire specifically, and past societies more broadly. The conquest of modern-day Wales began in AD 47/48 with the Roman campaign against the Deceangi tribe to the north. This was followed by campaigns against the Silures in the south-east and tribes in the west. By AD 78, Wales was completely subjugated. As part of this subjugation process, Roman roads were constructed across Wales. With the piecemeal conquest of Wales, roads are suggested to have first been constructed along the eastern-most edge from the Roman fortress at Wroxeter to the south. After AD 69, additional roads, totalling an estimated 1100 km in length, were constructed to the west (Fig. 2) (Arnold and Davies, 2000; Burnham and Davies, 2010).

In contrast to assuming the influence of slope gradient on movement is uniform across multiple roads, we estimate the influence of slope gradient on the position of individual Roman roads using least-cost path (LCP) analysis (Lewis, 2021) and likelihood-free Approximate-Bayesian Computation (Beaumont, 2019). An LCP is the path that minimises the accumulated cost between a pre-defined origin and destination location within a raster grid. The cost of movement most often represents time-taken or energy-expended when traversing slope gradient (Lewis, 2024a). The terrain of Wales is represented by the Ordnance Survey 50 m Digital Elevation Model (DEM) (Ordnance Survey, 2023), while LCPs were calculated using the R package *leastcostpath* (Lewis, 2023). Here ABC estimates the influence of slope gradient for each Roman road by simulating a high number of possible roads reflecting different rules drawn from a prior distribution. Associated rules, for example a high preference for shallow slope gradients, are accepted for a specific road if the simulated roads are sufficiently similar in their position. These accepted rules approximate the posterior distribution. Those simulated roads, and their associated rules, not similar to the specific Roman road are hence rejected. The target rule of interest is the influence of slope gradient measured by parameter b, or the rate of decline from the maximum influence of slope gradient (Supplementary Fig. 1). A parameter b value of 0 is the functional baseline and indicates that the influence of slope gradient does not decline with increasing slope gradient. In this case, slope gradient has no influence on the position of a Roman road, with the Roman road expected to be constructed as a straight feature, assuming a preference for straightness. Higher parameter b values, in contrast, reflect that the rate of decline from the maximum influence of slope gradient is steeper, with the position of a Roman road more influenced by a preference for shallower slope gradients. While b is theoretically unbounded at the upper limit, increasingly high values approach a hard-limit threshold where all slope gradients greater than 0 are penalised. The influence of slope gradient on roads as detailed in previous studies are estimated using slope-based limits and denoted by b_{lim} (See 'Materials and Methods'). Here, reported slope gradient of a road in previous studies is assumed to approximate the critical slope gradient, or the maximum slope gradient at which it becomes more economical to use switch-backs than directly traverse the slope gradient. A slope gradient of 15% is, for example, suggested to be ascendible/descendible directly by a wheeled vehicle, given the mechanical properties of Roman vehicles (Raepsaet, 2002; Verhagen and Jeneson, 2012). For a critical slope gradient to occur at 15%, a b_{lim} value of 6.7 is required. Likewise, a b_{lim} value of 11.1 is required for a critical slope gradient at 9%, or that which is ascendible/descendible directly by a loaded wheeled vehicle drawn by two mules (Verhagen and Jeneson, 2012) (Supplementary Fig. 1).

This study has three objectives: First, to demonstrate the feasibility of the generative inference model for estimating the influence of slope gradient on past roads via both a simulated (Supplementary Figs. 2–4) and a Roman case study. Second, to quantify whether and how the position of Roman roads in Wales is influenced by different rules. And third, to relate the estimated influence of slope gradient to road straightness, offering a unified, comparative framework for inferring the motivations for road construction in past societies.

Materials and methods

Data and code associated with this study are permanently archived at Lewis (2026).

Roman roads in Wales

The positions of known and conjectured Roman roads in Wales were based on Historic Environment Records (HER) as supplied by the regional Welsh Archaeological Trusts (Clwyd-Powys, Dyfed, Glamorgan-Gwent, and Gwynedd). The positions of these Roman roads were manually amended to include only the 62 known Roman roads in Wales as documented in the 'Roman frontiers in Wales and the Marches' (Burnham and Davies, 2010). The position of individual roads included within this analysis are those that show extant earthworks such as quarry pits or the agger (the embankment of the road), or well-recorded buried features (Burnham and Davies, 2010). To reduce uncertainty in the analysis, roads with less substantive evidence, or those conjectured, were not included.

Hierarchical movement model

The influence of slope gradient on the position of both the 62 known Roman roads and the simulated routes was estimated using a Bayesian hierarchical movement model. This influence was modelled as an exponential (*Laplace*) function defined as follows

$$TC_{iexp}(-b_i * |(x + 0.05)|)$$

$$b_i TruncNorm(\overline{b}, \sigma)$$

$$\overline{b} TruncNorm(1, 10)$$

$$\sigma Exponential(1)$$

where TC_i is the influence of slope gradient on the position of individual Roman road i in Wales, x is the mathematical slope gradient, b_i is the rate of decline from the maximum influence of slope gradient, $\overline{b}$ is the rate of decline from the maximum influence of slope gradient on the position of Roman roads at a population-level, and σ is the standard deviation for the rate of decline from the maximum influence of slope gradient on the position of Roman roads at a population-level.

Priors are weakly informative and set to realistic ranges. For example, restricting to positive-only values ensures that the influence of slope gradient on the position of roads cannot increase with steeper slope gradients. To establish the robustness of the hierarchical movement model for inferring the influence of slope gradient on roads, a dataset of comparable sample size ($n = 62$) was simulated. The hierarchical model was deemed robust, with the majority (59 out of 62, 95.16%) of true parameters correctly estimated within the 95% credible interval (Supplementary Figs. 2 and 3). Those roads (3 out of 62) with true parameters not correctly estimated by the hierarchical model had an average absolute difference of 0.06.

Least-cost path calculation

250,000 b_i parameter values drawn from $\overline{b}$ and σ were used to calculate 250,000 TC_i. Each TC_i was used to calculate 250,000 conductance surfaces (the inverse of the more traditional cost surface) and least-cost paths for each Roman road (15,500,000 least-cost paths in total). Least-cost paths represent the optimal path between two locations using a conductance surface that quantifies the ease of traversing from one cell to each of its eight adjacent cells (Lewis, 2021). The terrain of Wales was represented by the Ordnance Survey 50 metre Digital Elevation Model (Ordnance Survey, 2023). Least-cost paths were calculated using the R package *leastcostpath* (Lewis, 2023) from the origin and destination points for each of the 62 Roman roads and simulated routes.

Parameter inference

b_i, $\overline{b}$, and σ parameter values for each of the 62 Roman roads and simulated routes were estimated using Approximate Bayesian Computation (Beaumont, 2019). Posterior distributions for each parameter were estimated by accepting 250 (0.1%) parameter values with the lowest Path Deviation Index value (Jan et al. 2000). The path deviation index quantifies the spatial separation between each least-cost path and its associated Roman road. The path deviation index is defined as follows

$$path\ deviation\ index = \frac{area\ between\ two\ paths}{Elucide\ and istance of the\ shortest\ path}$$

The index can be interpreted as the average distance between the two paths. Median Path Deviation Index across the 62 Roman roads ranges between 0.54 and 992.05, with an overall median of 171.65 (Supplementary Fig. 4). In total, 15,500 (250×62) least-cost paths and associated parameter values were accepted, with 15,484,500 least-cost paths and associated parameter values rejected.

Estimating b from theoretical slope-based limits

b_{lim} values for slope-based limits reported in prior studies were estimated using the *uniroot* function in the R package *stats*. Specifically, the rate of decline from the maximum influence of slope gradient for the two scenarios '*ascendible/descendible directly by a wheeled vehicle*' (parameter $b_{lim} > 6.7$) and '*ascendible/descendible directly by a loaded wheeled vehicle drawn by two mules*' (parameter $b_{lim} > 11.1$) was fit using the reported critical slope gradient values of 15% and 9% in Verhagen and Jeneson (2012); while the rate of decline from the maximum influence of slope gradient for the Roman road in Judea (parameter $b_{lim} = 5.6$) and its surrounding escarpment (parameter $b_{lim} = 2.8$) was fit using average slope gradient values of 18% and 36% in Har-El (1959). Proposed b values ranged from 0 to 250 and were fit as follows

$$pace = exp(-b * |(x)|)$$

where x is the mathematical slope gradient ranging from -0.9 to 0.9 at increments of 1e-6.

The critical slope gradient was calculated for each potential *pace* function as the slope gradient at which the *pace* height gain rate is maximised (Supplementary Fig. 1). Slope gradients steeper than the critical slope gradient are difficult to traverse directly, with the use of zig-zags preferred (Llobera and Sluckin, 2007; Kay, 2012). It is, thus, assumed that the critical slope gradient or average slope gradient values can be used to estimate the rate of decline from the maximum influence of slope gradient (parameter b_{lim}).

Influence of slope gradient and road sinuosity relationship

The 'influence of slope gradient' and 'road sinuosity' relationship was modelled using a linear Bayesian regression with the R package brms (Bürkner, 2017) as follows

$$road\ sinuosity \sim rate\ of\ decline\ from\ maximum\ influence\ of\ slope\ gradient\ (median\ parameter\ b) + median\ terrain\ ruggedness + median\ road\ length$$

$$\text{road sinuosity} \sim \text{rate of decline from maximum influence of slope gradient (median parameter b)} + \text{median terrain ruggedness} + \text{median road length}$$

$$\text{Default priors : flat prior for parameter b and terrain, ruggedness;}\ student - t(3,\ 1.1,\ 2.5)\ \text{for Intercept;and student} - t(3,\ 0,\ 2.5)\ \text{for Sigma}$$

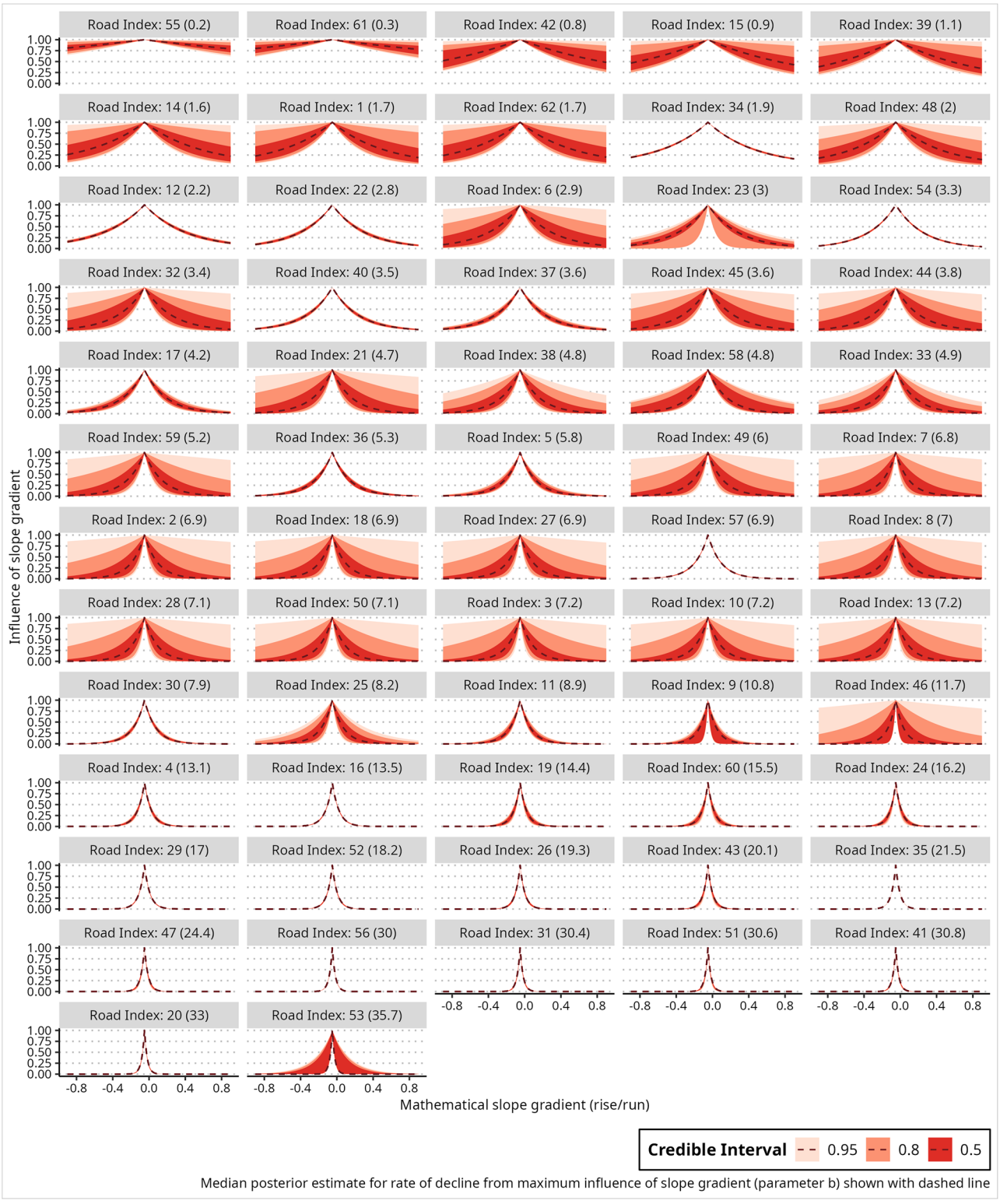


Fig. 3 Influence of slope gradient on Roman roads. Posterior estimates for the rate of decline from the maximum influence of slope gradient (parameter *b*) for individual Roman roads. Credible intervals denote the probability that the estimated *b* value is within this range. Median posterior estimates for parameter *b* are shown in brackets. Road indices correspond to those in Fig. 2.

We ran 10,000 iterations and four chains for each of the two linear models. The two models include: (1) estimated influence of slope gradient (median parameter *b*) and median road straightness for all 62 Roman roads accounting for

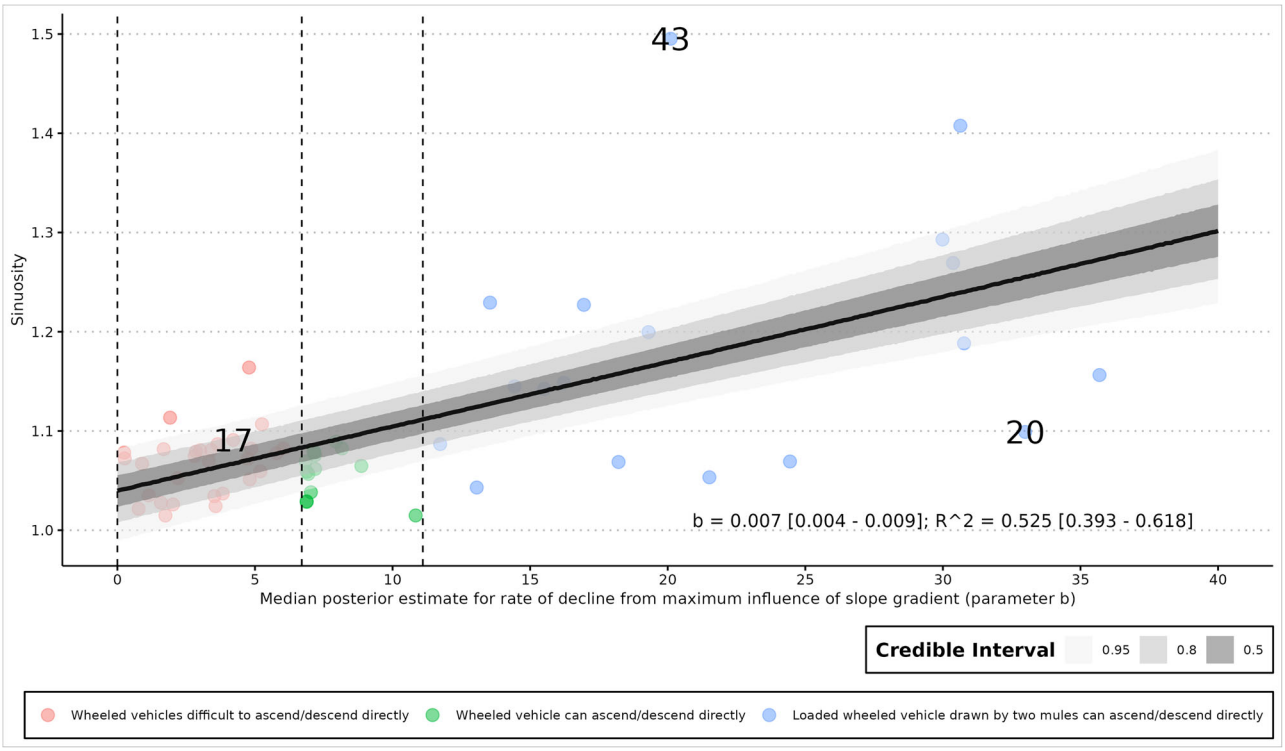


Fig. 4 Influence of slope gradient and road sinuosity relationship. Median posterior estimates for the rate of decline from the maximum influence of slope gradient (parameter *b*) and median sinuosity for individual Roman roads, accounting for measurement error in parameter *b* and controlling for terrain ruggedness and road length. Predicted road sinuosity values for increasing rate of decline from the maximum influence of slope gradient (parameter *b*) are shown with grey credible intervals. Unique numbers correspond to road index values mentioned in text.

measurement error in parameter *b*; and (3) estimated influence of slope gradient (parameter *b*) and road straightness for Roman roads whose parameter *b* does not includes both '*Wheeled vehicles difficult to ascend/descend directly*' and '*Wheeled vehicles can ascend/descend directly*' and accounting for measurement error in parameter *b* (Supplementary Figs. 5 and 6). Median terrain ruggedness within a 1 km buffer-distance of each Roman road was calculated using the *terrain()* function in the R package *terra* (Hijmans et al., 2026) following Wilson et al. (2007). Median road length was calculated using the *st_length()* function in the R package *sf* (Pebesma and Bivand, 2023) for all accepted (15,500) least-cost paths. Road lengths for each Roman road section were subsequently mean-averaged. Measurement error in parameter *b* as represented by the standard deviation of the posterior distribution for each modelled Roman road was accounted for using the *me()* function in the R package *Brms* (Bürkner, 2017). Convergence of the chains for each model was checked using the Gelman-Rubin diagnostic (Rhat < 1.01) and visual inspection of the trace plots.

Results

Influence of slope gradient variability

Results reveal substantial variability in the influence of slope gradient on the position of Roman roads in Wales (Fig. 2). Median posterior estimates for the rate of decline from the maximum influence of slope gradient (parameter *b*) on individual roads range between 0.25 and 35.69 (Fig. 3 and Supplementary Fig. 1), with lower *b* values indicating that slope gradient has less influence on the position of a Roman road. Median posterior estimate

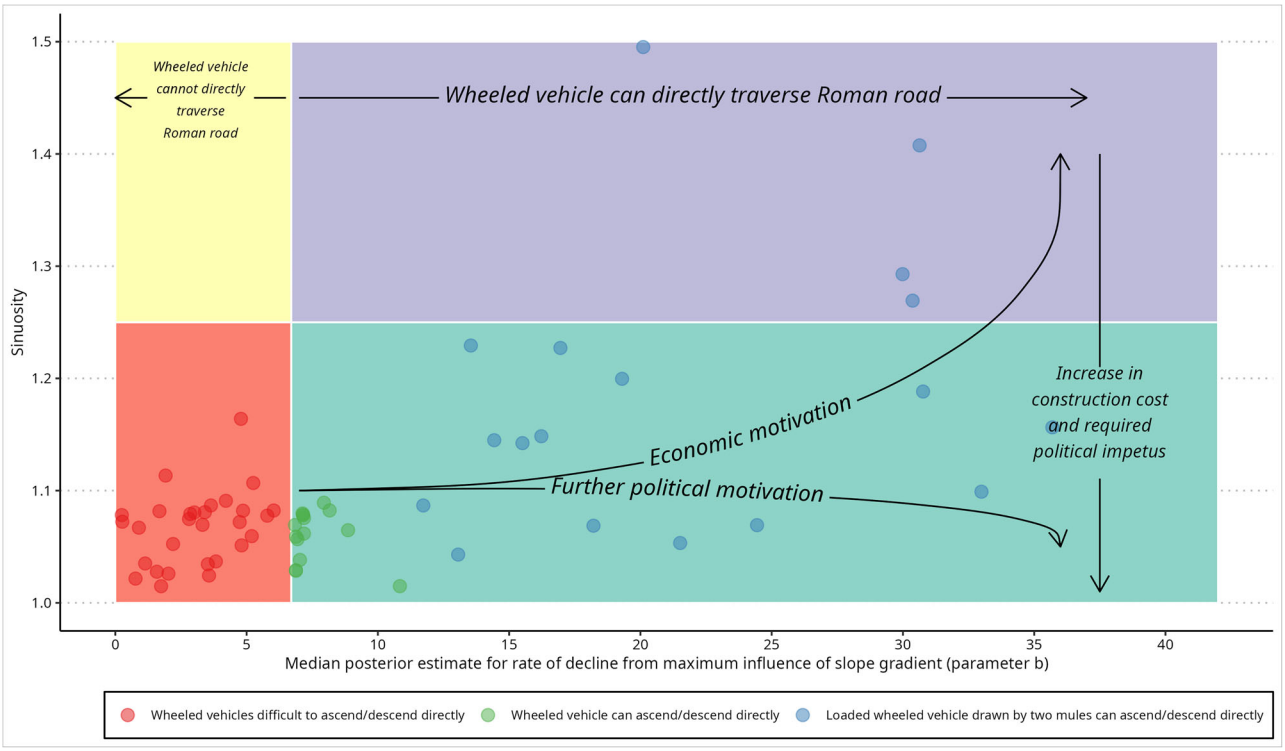


Fig. 5 Four qualitative quadrants for the influence of slope gradient and road straightness relationship. Top-left quadrant shown in yellow (*low b, high sinuosity*) contains roads that deviate from straightness despite the lower influence of slope gradient; bottom-left quadrant in red (*low b, low sinuosity*) contains straighter roads with lower influence of slope gradient; top-right quadrant in purple (*high b, high sinuosity*) contains roads that deviate from straightness with higher influence of slope gradient; and bottom-right quadrant in green (*high b, low sinuosity*) contains straighter roads with higher influence of slope gradient. Roads in *top-left* and *bottom-left* quadrants readily facilitate those on foot, pack animals, but not wheeled vehicles without additional support. Roads in *top-right* and *bottom-right* quadrants readily facilitate those on foot, pack animals, and wheeled vehicles.

for the rate at a population-level ($\overline{b}$) is 6.31 with a median standard deviation (σ) of 0.76 ($\overline{b}$ = [0.27–35.60, 95% Credible Interval]; σ = [0.03–3.86]).

Nearly half (46.8%, 29 out of 62) of the modelled Roman roads in Wales have a median posterior estimate for the rate of decline from the maximum influence of slope gradient (parameter b) that falls below the threshold necessitated by wheeled vehicles (parameter $b_{lim} \leq 6.7$) (Fig. 4). Sinuosity for these 29 roads ranges from 1.01 to 1.16, with a median of 1.07. Sinuosity here refers to the length of the road divided by its '*as the crow flies*' straight-line distance. A sinuosity value of 1.07, for example, indicates that the length of the road is 107% the length of its straight-line distance; roads with sinuosity values closer to 1 are straighter. 33 Roman roads (53.2%) have an estimated median parameter *b* that exceeds the threshold required for wheeled vehicles to directly ascend and or descend slope gradients (parameter $b_{lim} > 6.7$). Within this subset, 18 roads (54.5%) can also ascended or descended directly by a loaded wheeled vehicle drawn by two mules (parameter $b_{lim} > 11.1$).

Overall, sinuosity of modelled Roman roads in Wales correlates positively with increasing rate of decline from the maximum influence of slope gradient (parameter *b* posterior), accounting for measurement error in parameter *b* and controlling for both terrain ruggedness and road length ($\beta_1 b = 0.007$ [0.004–0.009, 95% Credible Interval]; explained variance, $R^2 = 52.5\%$ [39.3–61.8% CI]). This relationship is robust when also accounting for uncertainty in the estimated parameter *b* values for each road, i.e. removing roads from the analysis whose parameter *b* includes both '*Wheeled vehicles difficult to ascend/descend directly*' ($b_{lim} \leq 6.7$) and '*Wheeled vehicles can ascend/descend directly*' ($b_{lim} > 6.7$) ($\beta_1 b = 0.006$ [0.003–0.009]; $R^2 = 0.508$ [0.304 –0.642]) (Supplementary Fig. 5 and Supplementary Fig. 6).

Discussion

The first conclusion that can be derived from the results is that slope gradient did not exert a uniform influence on Roman roads in Wales, nor did roads conform to a single unifying preference for straightness. This variability in the *straightness-gradient* trade-off is suggested to reflect that the construction of individual roads was conditioned by distinct political and economic motivations.

More general patterns have, nevertheless, emerged from the comparative analysis of multiple Roman roads within a single hierarchical model.

Overall, the influence of slope gradient on Roman roads in Wales is below the functional threshold necessitated by wheeled vehicles (median $\overline{b} = 6.31$). Specifically, it is lower than the minimum b value that can be directly traversed by a loaded wheeled vehicle drawn by two mules ($b_{lim} = 11.1$) and the minimum b value that can be directly traversed by a wheeled vehicle ($b_{lim} = 6.7$). This difference indicates that traversing a typical Roman road in Wales with a wheeled vehicle would have presented significant logistical difficulties. Evidence of wheel-ruts on multiple roads in Wales, however, attest to the use of wheeled vehicles (Evans et al., 2010). Given that the observed $\overline{b}$ value indicates that a typical Roman road in Wales did not readily facilitate the use of wheeled vehicles, additional support would have been required. To overcome the mechanical limits of wheeled vehicles, draught power would have been supplemented by the use of manpower from the army, local peoples, and enslaved peoples (Margary, 1973); as well as the requisition of additional oxen, horses, and pack-mules (Kendal, 1996).

The *straightness-gradient trade-off* across multiple Roman roads in Wales can more generally be related to the political and economic motivations for road construction in the Roman Empire specifically and past societies more broadly. This is summarised by four qualitative quadrants (Fig. 5). First, while none occur in the study region of Wales, Roman roads in the top-left quadrant (*low b, high sinuosity*) can be interpreted as roads that were influenced less by slope gradient, but nonetheless deviated from straightness. Roads in this quadrant can readily facilitate those on foot, pack animals such as mules and oxen, but not wheeled vehicles. In less rugged terrains, where there are fewer topographic constraints that would cause the road to deviate from straightness, deviation from straightness indicates that additional factors besides slope gradient are influencing the position of roads. Potential factors include physical barriers such as marshlands, watercourses, and forests, and cultural barriers such as territorial boundaries, social divisions, and areas of taboo. The presence of unaccounted-for 'attractors' such as habitational settlements, religious sites, and economic sites, including mines and agricultural areas, could also influence the position of roads to deviate from straightness. Multiple Inka roads, for example, deviate around terracing constructed by the Pre-Inka, Wari empire (Schreiber, 1992). Without these additional factors, it is, following the assumption that past roads prioritised straightness, expected that a past road would not deviate substantially from straightness unless required. When terrain did not necessitate deviation, Roman roads were constructed as straight features within the landscape (Bekker-Nielsen, 2000). The Via Flaminia in Roman Italy is, for example, noted for its straightness at the expense of pre-existing settlements (Perkins, 1957) (Fig. 1). Inka roads, likewise, were straighter in less rugged, coastal regions than the more rugged highlands (Hyslop, 1984). Past roads in more rugged terrains are also less likely to be in this quadrant, given that if slope gradient has less influence on the position of a road, straightness will be preferred. Preference for straightness is, however, still conditioned by terrain: straight roads are more difficult to construct as terrains become more rugged. A Roman road ('Scorpions' Ascent) in Roman Judea (Fig. 1), for example, while possessing slope gradients shallower than the surrounding escarpment as a result of zig-zags and the construction of steps cut into the rock ($b_{lim} = 5.6$ versus $b_{lim} = 2.8$), remained sinuous and functionally restricted to camels and those on foot (Harel, 1959). Further modification to the landscape for the construction of a road that was both straighter and could facilitate wheeled vehicles ($b_{lim} > 6.7$) would have required additional expense and greater political impetus (see *bottom-right quadrant*).

Second, those roads in the bottom-left quadrant (*low b, low sinuosity*) can be interpreted as roads whose construction was influenced less by slope gradient and, in contrast to the top-left quadrant, did not deviate substantially from straightness. In less rugged terrains, this is to be expected, given that there would be fewer topographic constraints that would cause the road to deviate from straightness. Roads in more rugged terrains that are straighter but less influenced by slope gradient are suggested to have been constructed to readily facilitate movement for those

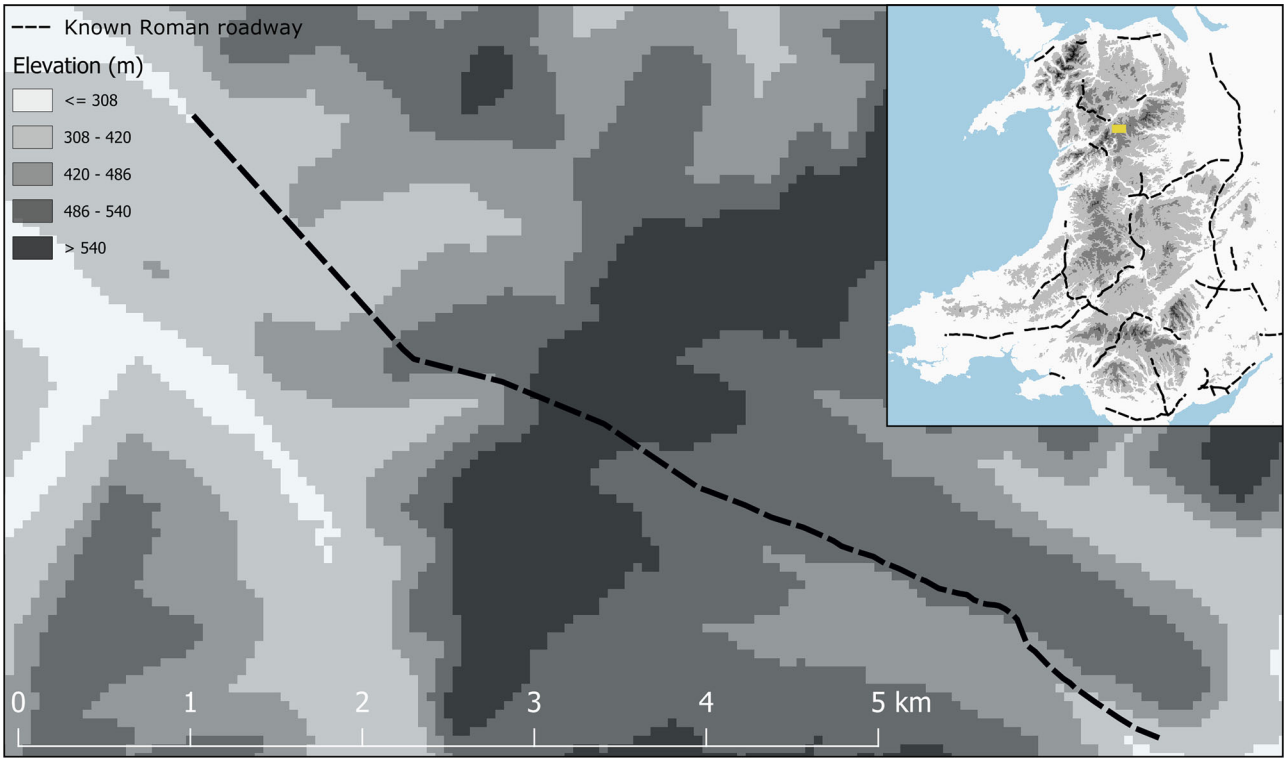


Fig. 6 A section of Roman road from the Roman fort at Caersws to Caer Gai. *Roman Road section 17* crosses steep slope gradients and is suggested to have been used solely by those on foot and horseback. Inset shows Roman roads in Wales and the location of *Road 17* in yellow.

on foot and pack animals, but not wheeled vehicles. That is, roads that more readily facilitate wheeled vehicles would be reflected by being sufficiently influenced by slope gradient ($b_{lim} > 6.7$). *Road 17* (Fig. 6), for example is suggested to have been used solely by those on foot and horseback given its steep slope gradient (Putnam and Toller, 2001), with this further corroborated by the road being placed within the bottom-left (*low b, low sinuosity*) quadrant (median posterior $b = 4.21$) (Fig. 4). Similarly, both Hopi and Miwok trails used by those on foot in north-eastern Arizona and California, respectively, are characterised as straight features, passing directly over rugged terrains (Barrett and Gifford, 1933; Ferguson et al., 2009). As with Inka roads (Hyslop, 1984), the absence of wheeled vehicles did not necessitate the construction of trails more influenced by slope gradient, i.e. those possessing a parameter $b > 6.7$. Only later with the introduction of wheeled vehicles did Hopi trails prioritise shallower slope gradients at the expense of straightness (Ferguson et al., 2009). For these later Hopi trails, this would be reflected in both higher parameter b and sinuosity values, i.e. these trails would transition into the top-right quadrant.

Third, those roads in the top-right quadrant (*high b, high sinuosity*) can be interpreted as roads whose construction was sufficiently influenced by slope gradient to facilitate wheeled vehicles but deviated from straightness. Roads in less rugged terrains are less likely to be in this quadrant, given that there would be fewer topographic constraints that would necessitate the road to be less straight and be more influenced by slope gradient. In contrast, more rugged terrains possess a greater number of topographic constraints that could cause the road to deviate from straightness. Roads that deviate from straightness but are sufficiently influenced by slope gradient to facilitate the use of wheeled vehicles are suggested to reflect predominately economic motivations. Here, economic motivations principally include the transportation of heavy goods such as natural metals and building materials, which is made easier when the road more readily facilitates the use of wheeled vehicles. In Wales, *Road 43* provides a clear example of this economic prioritisation (Fig. 7). Connecting gold mines to a south-eastern Roman fort, this road follows a circuitous route in the landscape (estimated median sinuosity = 1.5, or 150% the length of its straight-line distance), with the position of the road sufficiently influenced by slope gradient to facilitate the use of loaded wheeled vehicles (median

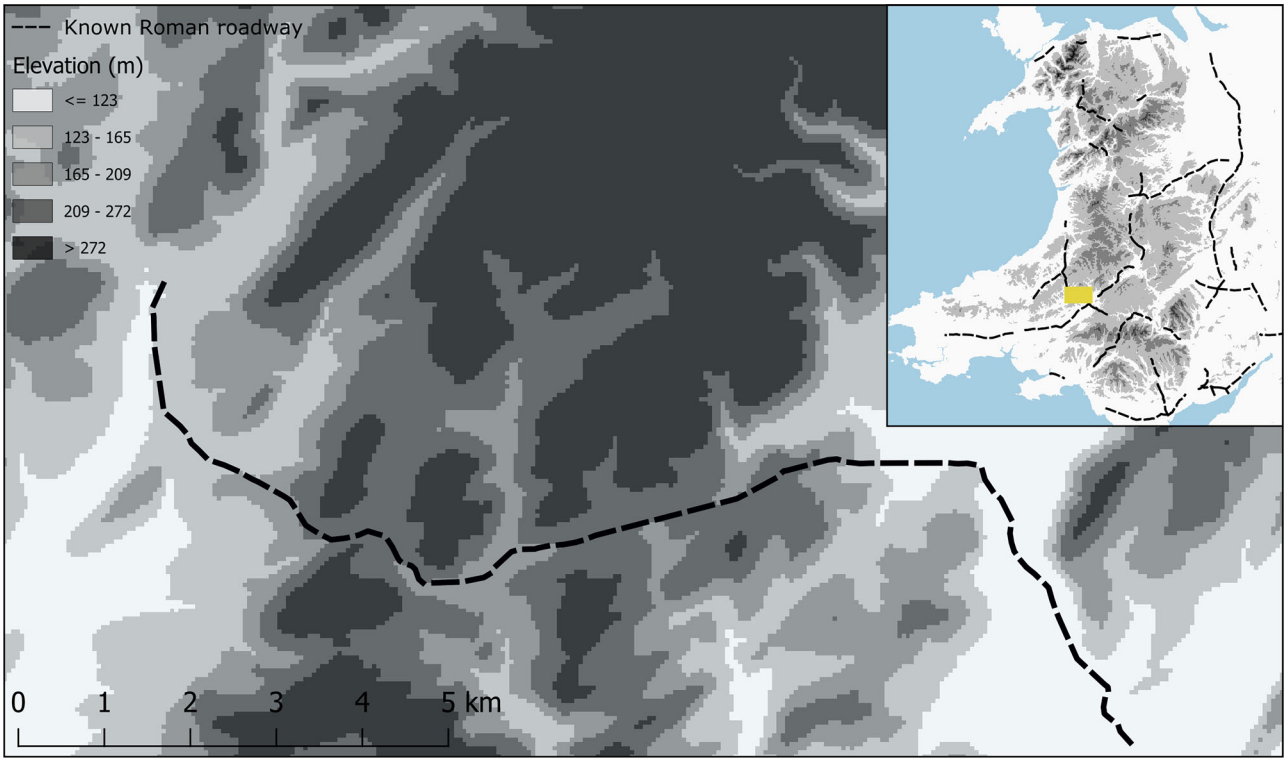


Fig. 7 A section of Roman road from the gold mine at Pumsaint to the Roman fort at Llandovery. *Roman Road section 43* follows a circuitous route in the landscape to facilitate the use of wheeled vehicles for the transportation of gold. The inset shows Roman roads in Wales and the location of *Road 43* in yellow.

posterior $b = 20.11$) (Fig. 3). With the Roman road connecting gold mines, this road was likely used by loaded wheeled vehicles to transport gold, as previously suggested by Burnham and Burnham (2004). Transporting gold did not, however, warrant reducing the sinuosity of the road–a more sinuous road that facilitated wheeled vehicles was deemed sufficient for this purpose. By way of contrast, Chacoan roads in the Chaco Canyon are deemed to not to have had an economic function, given that they ignored topographic constraints and did not facilitate travel in difficult terrain (Vivian, 1997). With Chacoan roads constructed as straighter features far beyond the physical requirements for those on foot only, a political explanation has instead been proposed (Vivian, 1997) (see below, *bottom-right quadrant*).

Lastly, those roads in the bottom-right quadrant (*high b, low sinuosity*) are interpreted as roads whose construction was both straighter and sufficiently influenced by slope gradient to readily facilitate wheeled vehicles. Roads in less rugged terrains are more likely to be in this quadrant, that is with fewer topographic constraints a road is more likely to both facilitate wheeled vehicles and be straighter. In contrast, roads in more rugged terrains are less likely to be in this quadrant, given the additional construction cost and labour mobilisation required to overcome the greater number of topographic constraints that impede straightness. That some roads are both sufficiently influenced by slope gradient to facilitate wheeled vehicles and are straight in these more rugged terrains suggest a further political motivation that exceeds an economic motivation alone. *Road 20* provides an example of this (see Figs. 2 and 4). Originating in the pre-Roman Iron Age and later re-used in the Roman period, this road has been associated with two potential functions: the movement of royal families, and the exchange of foodstuffs and minerals (Malim and Hayes, 2010). With road straightness not a prerequisite for transporting foodstuffs and minerals, as demonstrated by *Road 43* in the top-right quadrant, the construction of *Road 20* is interpreted here as having political benefits beyond purely economic utility, namely its association with royal families of the Iron Age. That is, like Chacoan roads, *Road 20* is straighter than required for the purpose of exchange: a less straight road (for example, those placed within the top-

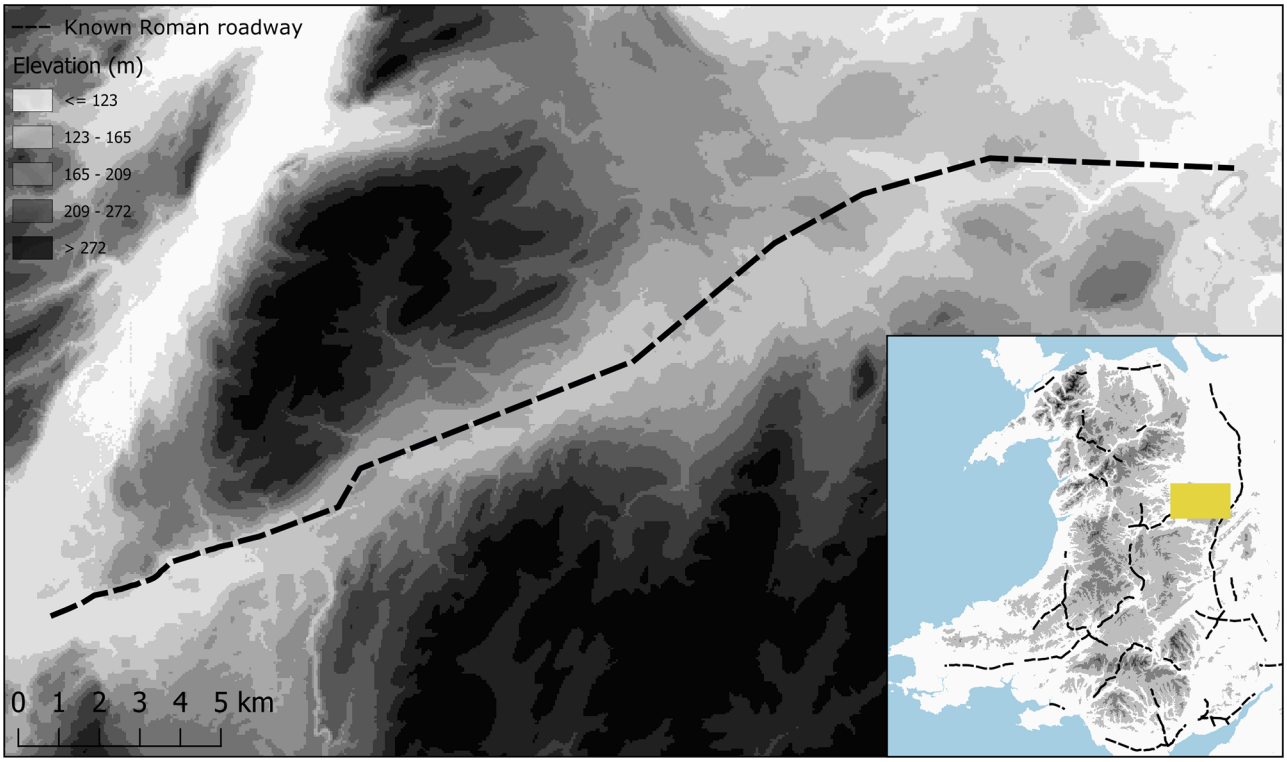


Fig. 8 A section of Roman road from the Roman fortress at Wroxeter to the Roman fort at Forden Gaer. *Roman Road section 20* follows the straight route in the landscape between two surrounding hills. Inset shows Roman roads in Wales and the location of *Road 20* in yellow.

right quadrant) would have been sufficient for the transportation of foodstuffs and minerals. Note, however, that the surrounding terrain further facilitates the construction of a straighter road (Fig. 8).

Nevertheless, the political motivation for *Road 20* is further attested by it receiving an all-weather surface in the pre-Roman Iron Age–an exceptionally rare feature for roads outside of towns at this time in Britain (Malim and Hayes, 2010). Only later, in the Roman period, was *Road 20 repurposed* for the movement of the army and their military supplies and foodstuffs into the centre of Wales (Burnham and Davies, 2010). Wheel-ruts, for example, have been found in the all-weather surfaces constructed during the Roman period (Malim and Hayes, 2010).

More broadly, modelled Roman roads in Wales that readily facilitate wheeled vehicles (parameter b value > 6.7) are shown to be less straight (Fig. 4). More sinuous Roman roads that facilitate wheeled vehicles (*top-right quadrant*) can be interpreted as roads whose justification for construction is economic, such as for the transportation of natural metals. Meanwhile, roads that are both straighter and readily facilitate wheeled vehicles (*bottom-right quadrant*) reflect further political motivations for their construction, e.g. *Road 43* versus *Road 20*. Roads whose construction was principally motivated by economic reasons are suggested to have lacked the necessary political impetus to have prioritised straightness, namely the removal of topographic constraints that would necessitate a road to deviate from straightness. This is in contrast to roads whose construction was also politically motivated, whereby straightness would have been further prioritised. Witcher (1998), for example, suggests that Roman roads in Britain were an active tool of imperialism that embodied Roman ideology, power, and identity: straightness, in particular, was a direct statement of power and a subjugation of nature. Petts (1998) similarly suggests that the straightness of Roman roads projected an ideology of dominance in contrast to the more sinuous pre-Roman routes. Modifications to the landscape to prioritise road straightness would have included stairways, embankments, and cut-and-fill (Chevallier, 1976). Given that these modifications could be expensive and would have required a mobilised labour force, the construction of straighter roads, all else being equal, is expected to be more likely with greater political impetus, culminating with the involvement of the Roman Emperor (Kissel, 2002). This ‘political impetus’ is expected to be statistically reflected

in a weaker relationship between the influence of slope gradient and road straightness (Fig. 4). While not in Wales, the modification of two Roman roads in Italy illustrates this transition from functional necessity to political monumentality (Fig. 1). The *Via Flaminia*, originally a military road connecting *Rome* to *Rimini* on the Adriatic coast (Ashby and Fell 1921), was modified by the Emperor *Vespasian* in AD 76/77 with a 38-metre-long road tunnel to bypass a step, narrow section. Similarly, the Emperor *Augustus* commissioned a 700-m-long road tunnel between *Naples* and *Pozzuoli* in 37 BCE to shorten the route and avoid steep slope gradients (Busana, 1997). In both cases, the investment required to maintain a straight road that facilitates wheeled vehicles reflects a political priority that transcended basis logistical needs.

At a societal level, the relationship between slope gradient and straightness serves as a proxy for political impetus. Past societies that construct roads for political reasons are expected to exhibit a weaker relationship between slope gradient and straightness than those that construct roads for economic motivations alone, all else being equal. With increased political motivation for road construction and the subsequent greater mobilised labour force, roads can be both straighter and shallower. As a corollary, Arden et al. (2025) have recently suggested that a Mayan road deviated from straightness as a result of local resistance, where forced labourers purposeful underperformed engineering tasks as a way to undermine state ideology.

While not feasible in this study given limited information on the diachronic development of Roman roads in Wales, it is expected that the influence of slope gradient on Roman road construction will increase over time to more readily facilitate wheeled vehicles. Roman Roads in Italy are, for example, suggested to be shallower than those constructed in the pre-Roman Archaic period (Tuppi, 2014). Likewise, it is expected that the straightness of a Roman road will reflect the specific political needs of individuals at the time of its construction. As mentioned previously, the construction of the Roman *Via Appia* is suggested to reflect the sponsors' need of patronage (Macbain, 1980) (Fig. 1). Moreover, it is expected, and as exemplified by the pre-Roman Iron Age and later re-purposed in the Roman period *Road 20*, that pre-existing roads will be re-purposed if the road meets the required function. For example, *Road 20* has been proposed here to have been constructed for its political benefits in the Iron Age and later re-used for the movement of the army in the Roman period. Both functions could, however, be met, given that the road was shallow enough to facilitate the use of wheeled vehicles. In cases when a function cannot be met, it is proposed that individual roads will either: (1) adapt to the terrain differently to meet the new function e.g. increase the influence of slope gradient (higher parameter b value, $b > 6.7$) to more readily facilitate the use of wheeled vehicles; or (2) re-use a pre-existing road but modify the terrain to meet the required function, e.g. level the terrain to more readily facilitate wheeled vehicles. Modifying a pre-existing road is, however, suggested to be more costly and therefore require greater political impetus than choosing a different route in the landscape. Following the *straightness–gradient* trade-off, it is thus predicted that the road adaptation scenario—at the level of a past society—will result in roads that are less straight, but can more readily facilitate wheeled vehicles (*top-right quadrant*). In contrast, the road modification scenario will result in roads that are straighter while also facilitating the use of wheeled vehicles (*bottom-right quadrant*). This is, however, all contingent on a past societies' population size; their labour dynamics, e.g. whether they practiced unpaid forced labour; and the length of time required to construct the road. It is, for example, possible for past societies with larger population size to mobilise a larger labour force towards road construction. This ability for greater mobilisation has also been related to the socio-political complexity of a past society (Earle, 1991). The *straightness–gradient* trade-off is, however, also dependent on the transportation technology within a past society. Roads sufficiently influenced by slope gradient to facilitate the use of wheeled vehicles (*top-* and *bottom-right quadrant*) are not required if the past society does not use wheeled vehicles, e.g. the Inka Empire (Hyslop, 1984) or the Chacoans (Vivian, 1997).

Despite the explanatory power of the quadrant-model, limitations remain. The current analysis cannot, for example, yet account for the 'attractors' and 'constraints' that might influence a road to deviate from straightness despite the low influence of slope gradient (*top-left quadrant*). Likewise, the hierarchical framework should be applied to other provinces in the Roman Empire, and other past societies more generally, to further assess both the variability in the *straightness-gradient* trade-off and for inferring motivations for the construction of past routes. While the 50 m resolution of the DEM used in this study aims to sufficiently capture the main processes influencing movement choice (Lewis, 2024b), future studies could further benefit from high-resolution LiDAR data. Increased DEM resolution

would allow the model to account for micro-topographies not currently represented, such as narrow terrain passages or archaeological features. Refining the cost surface to account for additional factors such as hydrological barriers also remains a priority.

Nevertheless, the analyses presented in this study reveal that even within a localised region of the Roman Empire, the *straightness-gradient* trade-off varies considerably across Roman roads. While variation in this trade-off across Roman roads can be attributed to the specific political and economic motivations for their construction, this trade-off provides insight into the motivations for past road construction. By establishing a functional measure for the influence of slope gradient on Roman roads, we provide a mechanism to distinguish between past roads constructed to readily facilitate wheeled vehicles for economic purposes and those that are also influenced by political motivations. The simulation-based, hierarchical generative inference model approach introduced here also offers a robust, unified, and comparative framework for evaluating broader hypotheses on motivations for road construction in the Roman Empire and past societies more broadly.

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Author contributions JL conceptualised the study, developed the methodology, wrote and edited the manuscript, produced the visualisations, and acquired funding. ERC assisted in the development of the methodology, provided supervision, and edited the manuscript.

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Data availability Data and code required to reproduce the analyses are permanently archived at https://doi.org/10.5281/zenodo.20759996.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval and consent to participate This article does not contain any studies with human participants performed by any of the authors.

Informed consent This article does not contain any studies with human participants performed by any of the authors.

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