
Utilising Supervised Parametric Classification to Assess the Quality of the UK Rural Road Network using Aerial LiDAR Data

201374125

Abstract

An automated method for the identification of rural road geometric features is presented for use in a national rural road assessment in England. This method includes the use of LiDAR for height and road surface intensity information, as well as aerial imagery, and road centrelines enabling automated classification of road surfaces prior to road width extraction. The method presented ensures scalability, allowing for an extension beyond the 1km² area proposed, given existing data and suitable computational power. A unique classification method is proposed, utilising a linear probability model given points determined to be road surface, derived from the road centreline information, while implementing a sampling methodology which primarily reduces the computational overhead. Results were broadly assessed qualitatively and quantitatively giving around a 70% accuracy in road width measurements. Additional geometric features extracted from roads include the change in road elevation and road surface quality, derived through LiDAR data, and road bend sharpness, derived through the OS Road Centrelines data.

Keywords: LiDAR; Aerial Imagery; Linear Probability Classification; Rural Road Quality

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Definitions

- **Light Detection and Ranging (LiDAR):** similar to radar, a laser pulse is sent out of a transmitter on an aircraft or ground vehicle and the light is reflected back to a receiver.
- **Billion Vehicle Miles (BVM):** the total number of miles travelled by all vehicles divided by 1 billion. Typically all traffic is measured in vehicles miles.
- **Digital Terrain Model (DTM):** digital representation of the land surface topography without surface objects.
- **Digital Surface Model (DSM):** digital representation of the land surface capturing all natural and built features.
- **Social Mobility:** the movement of individuals, families, households, or other categories of people within or between social strata in a society.
- **Social Exclusion:** exclusion from the prevailing social system and its rights and privileges, typically as a result of poverty or the fact of belonging to a minority social group.
- **Read-eval-print loop (REPL):** a simple interactive computer programming environment that takes single user inputs, evaluates them, and returns the results to the user.
- **Root Mean Square Error (RMSE):** the square root of the second sample moment of the differences between predicted values and observed values. Commonly used to measure the difference between sample or population values.
- **Scalability:** the property of a system to handle an increasing amount of work. In this context, a methodology that may handle an increasing area of interest.

1. Introduction

ROAD usage in the United Kingdom has been steadily increasing by year with the highest ever billion vehicle miles travelled in 2018 (318.1 BVM; [Department for Transport 2019](#)). Characterised by tall hedgerows and winding turns, rural roads in the UK are often unsuitable for higher traffic flow due to the obstruction of view from protected hedgerows, narrow lanes and often poor condition ([Department for Transport 2018b](#)). Due to the abundance of these roads, with "Unclassified" local network roads making up 60% of all roads in the UK ([Department for Transport 2012](#)), and their varying nature, the national assessment of these roads into appropriate speed limits on an individual basis has been considered impractical ([Taylor et al. 2002](#)). Due to this, there have been no individual assessments for the majority of rural roads, and given their nature, are classified as unlit, single carriageway roads and thus assigned a default speed of 60mph ([UK Government 2019b](#)). Highways England manages the motorways and trunk roads within the UK, but local road networks are maintained by Local Authorities, and as such have no comprehensive information regarding these smaller road networks ([Highways England 2019](#)). Rural roads in the UK are often cited as by far the most dangerous road type with studies suggesting that up to two thirds of vehicle accidents occur on rural roads ([Corben et al. 2005](#)).

The Rural Urban Classification defines a rural area as one outside of a settlement with more than a 10,000 resident population ([UK Government 2011](#)), therefore a road could be considered rural, if either connecting or present within small settlements in the UK. This study will focus particularly on rural connecting roads, outside of rural towns.

A Governmental review of speed policy considered the need for the role of speed and accidents on rural roads to be further addressed (?), suggesting a framework for individual classification of roads, taking into account local considerations of the road to implement more suitable speed limits. In 2012, draft guidance for rural roads was presented by the Department for Transport suggesting a blanket reduction in rural single carriageway road speed limits from 60mph to 40mph including a reduction to 50mph for lower quality A and B roads ([BBC 2012](#)). However, this draft guidance has yet to be implemented, likely due to the costs involved in a blanket change to speed limits. For example, the cost for a complete change in national speed limits from imperial to metric in Ireland cost an estimated €30 million in speed limit signs alone ([Noctor 2004](#)). These costs suggest that an alternative to blanket implementation may be required.

National speed limits have seen little variation for a number of years, with the majority of roads following the broad criteria for the three main roads types. The three national speed limits are:

- the 30 mph speed limit on roads with street lighting (sometimes referred to as Restricted Roads)
- the national speed limit of 60 mph on single carriageway roads
- the national speed limit of 70 mph on dual carriageways and motorways.

([UK Government 2019b](#))

The [Department for Transport \(2013a\)](#) outline in *Setting Local Speed Limits*, that national speed limits

are not appropriate for all roads, where local road conditions present the requirement for alternative speed limits. The majority of the rural road network in the UK follows the national speed limit of 60mph for single carriageway roads, and 70mph for dual carriageway roads, despite driver speed often being far below the speed limit. Noted as especially common on C and Unclassified roads due to the narrow roads, frequent bends, junctions and access roads. In 2011, an estimated 66% of total road deaths in Britain occurred on rural roads, with 51% on single carriageway rural roads with the national speed limit of 60mph.

The Department for Transport (2013a) suggest that selecting alternative speed limits for single carriageway rural roads should consider:

- History of collisions;
- The road's function;
- Existing mean traffic speed;
- Use by vulnerable road users;
- The road's geometry and function;
- and the road environment, including road-side development

The Road Safety Management Capacity Review (Department for Transport 2018c) outlines the current limitations with road safety management, with the lack of defined and measurable safety performance framework, noting that such a framework should set out the long term goal of total prevention of road deaths and injuries, achieving this through a reduction in average speeds on different road types, and an improvement in emergency response times. This review states that at present there is a distinct lack of both urban and rural road hierarchies, which could be used to better match appropriate speed limits, with function, layout and design. Again, this review notes that posted speed limits often allow for speed far in excess of the design limits of single carriageway rural roads, with inappropriate but allowable speed often a contributing factor in rural accidents. Finally the report calls for a review of national speed limits as soon as possible.

A recent development for guidance in setting local speed limits is the production of the *Speed Limit Appraisal Tool* (Department for Transport 2013b). This tool provides an automated method for the introduction of new speed limits for local councils. This tool takes observed traffic flow, accidents, speeds, descriptive information regarding the network and current costs, outputting projections in these data to advise speed limit changes. While this tool introduces a quantitative method for individual road speed limit assessments, it misses some key features outlined in past government framework proposals (e.g. Department for Transport 2018c), particularly in relation to road geometry.

The methodology presented in this paper will focus particularly on the call for an improved understanding of rural road geometry to support the production of appropriate and justified speed limits for rural single carriageway roads. Road geometry is defined here as the parameters of roads relating to geometric design, particularly relating to the appropriate road speed, stopping sight distance, road width, road bends and surface quality (Jaakkola et al. 2008).

Some road geometric information may be extracted through the readily available OS Road centreline geometries, however, the extraction of road widths poses a complication as this information is not readily available, and automated extraction requires techniques that enable road classification through the data available, either aerial imagery, or LiDAR. In particular, road classification through LiDAR data has been explored as an alternative to aerial imagery classification, allowing for more reliable results due to the presence of additional information that LiDAR provides. The following section outlines LiDAR in this context, and presents how LiDAR may be used to extract these features of roads.

1.1. Introduction to LiDAR

LiDAR data is collected by emitting rapid laser pulses from an aircraft towards the ground which are reflected back, measuring the distance between the aircraft and surface objects at up to 500,000 measurements per second ([Environment Agency 2019](#)). This method produces a set of highly accurate three dimensional points which collectively are known as a LiDAR point 'cloud'. As LiDAR data detects all surface objects, the resultant point cloud produced will include all natural and man made structures, including buildings, roads, trees in addition to the natural variation in the terrain height, known as a digital surface model ([Hatger 2005](#)).

The main features unique to LiDAR, as opposed to similar aerial data collection techniques such as true colour imagery are outlined below:

- **Pulses:** LiDAR systems record the data by emitting a laser pulse which is reflected back at the aircraft by ground objects. If the laser hits a solid object such as ground or a building roof, this laser pulse is entirely reflected back towards the aircraft, giving a single point. However, if the laser pulse hits a soft object such as a tree canopy, the pulse may be partially returned, giving multiple return pulses ([Rottensteiner et al. 2003](#)). Therefore, these multiple pulse returns give information regarding objects at an exact x y location but with varying heights.
- **Intensity:** LiDAR systems also give intensity values for return pulses, which gives information regarding the reflectance of the surface of objects that are hit by the laser pulses. If intensity is given I then reflectance R may be represented as $R = \frac{I}{E_T}$ where E_T refers to the first pulse signal intensity ([Charaniya et al. 2004](#)).
- **Elevation:** In addition to x and y coordinates, the distance between the plane and the reflected ground or object is recorded and assigned a z value.

1.1.1. Benefits over Aerial Imagery

Rural roads in the UK are often characterised by dense hedgerows either side, with large oak trees that extend over the road surface. In addition to the reduction in corner visibility on these roads, standard aerial imagery suffers from the road surface being obscured by shadows from these trees and hedgerows, and the tree canopy itself. Additionally, aerial imagery often suffers from obstruction due to clouds ([Li et al. 2016](#)). Due to the inclusion of pulses with modern LiDAR data, the road surface can often be detected through the canopy by selecting the final pulse returns, the infrared laser pulses also have smaller shadows, due to the narrow scanning angle of LiDAR ([Wang & Shan 2009](#)). Non LiDAR imagery often suffers from scene complexity, where road patterns, vehicles and lane markings reduce road heterogeneity ([Li et al. 2016](#)).

The 3D z value information provided by LiDAR data allows for the separation of ground and objects on the surface, meaning roads and buildings are often easily separated, despite having similar reflectance ([Sampath & Shan 2008](#)). Additionally, the reflectance of roads is often homogeneous, and distinctly separate from vegetation ([Clode et al. 2004](#)).

1.1.2. Limitations

LiDAR lacks any texture or spectral information, and often studies in road classification have combined LiDAR with aerial imagery to alleviate this issue ([Hu et al. 2004](#), [Zhang et al. 2003](#)), with the inclusion of luminescence information to aid with road classification (e.g. [Charaniya et al. 2004](#)). LiDAR points are distributed irregularly and with varying density, with point density often higher where flight strips overlap, and tall objects can occlude points, leaving more limited data surrounding trees or buildings ([Li et al. 2016](#)).



Fig. 1.1: Study area highlighting road centrelines, each colour represents a separate 'road' as defined by the OS Data provided. Thicker roads are B roads, while thinner are Unclassified. The inset map gives shows an example road, with features typical of roads within this study area.

Often road classification methodologies use LiDAR height data to identify kerbs to separate streets from pavement (Kumar et al. 2013, Vosselman & Zhou 2009), however rural roads often have no kerb, and are at the same level as the surrounding vegetation if they are managed grass verges (Yadav et al. 2018).

LiDAR data often requires a large amount of processing due to the irregular distribution of points, presence of noise and the number of variables that have to be considered, Yadav et al. (2018) note that often papers do not include information regarding the computational time for processing this data which may cause practical limitations at larger scales.

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1.2. Objective of this paper

This paper will present a method for rural road classification and width extraction for a 1km² region in the North West of England. The methodology is produced in order to ensure scalability and automation, allowing for replication for any area where data is available. Data used will include road centreline geometries, LiDAR point cloud, and aerial imagery to extract road widths through linear probability models. Additionally, this paper aims to extract other features of roads such as elevation changes, surface quality, and the sharpness of bends. The extraction of such features aim to build upon past road classification studies, combined with a more refined methodology that aims to ensure a higher accuracy for rural British roads.

Key Aims:

- Produce and assess an automated method using LiDAR, aerial imagery and OS road geometry to determine the true width of roads within the chosen study area, outlining the particular limitations and solutions when considering the rural British road network.
- Using OS Road and LiDAR Data produce an automated method for determining the characteristics of roads that relate to overall road quality. These are;

Bend sharpness

Road steepness

Surface quality

- Using extracted road features, outline the overall quality of the road network, and allow for direct comparison between each road.

The site selected in this study was chosen to include a selection of B, and Unclassified local roads within a rural setting. Particularly the roads chosen are often partially obscured by tree canopies and do not have visible kerbs, both key features in rural British roads.

This paper is organised into chapters, first a literature review, outlining the broad implications of speed limits, rural road networks, and object extraction particularly in relation to LiDAR aerial point clouds. Second, a detailed description of the methodology involved in this paper will outline the techniques used to classify road widths, in addition to the other road geometric information. A results section will primarily assess the method for road extraction, through sensitivity analysis and some qualitative observations, a section will then explore the findings. Finally a discussion will detail the implications of the findings, and suggest areas for methodological improvement.

2. Literature Review

Typical road classification techniques have focused purely on urban road networks and involved methods which can be both computationally intensive and time consuming. Given the pressure for a full quantitative assessment of the current speed limits in the rural network in the United Kingdom, there is a demand to produce comprehensive methods for rural road feature extraction. This paper primarily focuses on techniques for assessing the road geometry for roads considered to be rural connecting roads in the United Kingdom. This literature review will first outline the current understanding of the rural road network, considering the role of speed and speed limits in accident likelihood, rural accessibility, and a detailed look at current road extraction techniques involving aerial imagery and LiDAR, presenting the key differences and limitations of these studies when considering the rural road network in the UK.

2.1. British Rural Road Network

Taylor et al. (2002) conducted a study outlining the key features of British rural roads, in an effort to improve the understanding of the characteristics associated with accident rates, beyond the past *Speed-accident relationship on European Roads* (MASTER) study which primarily consisted of European road data, with limited data for England (Baruya 1998). Taylor et al. (2002) identify key features of 174 selected rural British roads across England which they use to classify roads into certain categories, this data was obtained through drive through video recordings.

Notably, the features unique to rural roads were observed to be the land use either side of a road, consisting mainly of residential, farming, wooded, open or industrial. Verges consisting of grass verges, pavement, low banks, ditches or none. Roadside type including the most dominant vertical feature closest to the road, including trees which may overhang the road, hedges, banks, fences and so on. This study also manually measured the road width for each site, and to determine the "hilliness" of roads, the number of 10m contour lines crossed were counted to give the total change in height.

Taylor et al. (2002) found that the average width of British rural roads varied from 2m to 10.2m with a mean width of 6.5m. Most were two lane roads, however a small number were single track. The mean length of roads was 3km, around half the sites had more than 3 bends per km with 1 third showing 1 severe bend per km. Most roads were flat, showing less than a 10m rise per km. Key features of British rural roads are listed in Table 2.1.

Road quality in this assessment was determined through categorising roads into four key groups:

- **Group 1:** Roads which are very hilly, with a high bend density and low traffic speed. *These are low quality roads.*
- **Group 2:** Roads with a high access density, above average bend density and below average traffic speed. *These are lower than average quality roads.*

Table 2.1: Features Identified as Important to Rural Road Analysis (Taylor et al. 2002)

Type of data	Examples
Discrete data	Type of junction Minor junctions Accesses Number of bends, classified into: Sharp (warning signposts) Medium Slight
Semi-continuous data	Lighting Reflecting road studs Kerbs Number of lanes Road markings Land use
Continuous data	Visibility Verge width and type Roadside type

- **Group 3:** Roads with a high junction density, but below average bend density and hilliness, and above average traffic speed. *These are higher than average quality roads.*
- **Group 4:** Roads with a low density of bends, junctions and accesses and a high traffic speed. *These are high quality roads.*

This study therefore attempted to outline a rural road hierarchy in relation to road function, and certain road geometries, which addresses issues outlined in the Government's review of speed policy (?). However, due to the nature of the data collection for this study, time constraints mean that producing a full road hierarchy for all rural roads within England is impractical and requires a review of the methodology. Additionally the speed policy review notes that road hierarchies should inform appropriate speeds for each road.

2.1.1. Rural Speed Limits

Accidents on rural roads often occur within the 60 mph speed limit meaning a distinction between what is an appropriate speed should be made that does not relate to a given speed limit. Baruya (1998) suggest a distinction between both *excess* and *inappropriate* speed. *Excess* when driving above the speed limit, and therefore directly breaking the law, *inappropriate* speed; driving too fast for the conditions of the road, not necessarily above the speed limit, often considered dangerous driving. A study by the Department for Transport (2013a) assessed the impact of inappropriate speed on rural roads, which contributed to 20% of all crashes on minor rural roads with a 60mph limit, whereas excess speed only accounted for around 16% of collisions. An observation of 270 single carriageway rural roads in England found that the distribution of mean speeds was wide, and often significantly below the 60mph limit (Department for Transport 2006).

The Department for Transport found that rural roads account for around 66% of all road deaths, despite accounting for around 42% of the total distance travelled by all vehicles. Notably 51% of all deaths in Britain in 2011 occurred on rural single carriageway roads, with the national speed limit of 60mph (Department for Transport 2011).

2.1.2. Speed, Road Geometry and Accidents

Lowering the speed limit on roads has been shown to result in an overall reduction in the average speed of vehicles. Finch et al. (1994) found that a reduction in the speed limit of a road resulted in a mean speed reduction of around one quarter of the difference, noting that drivers will often obey speed limits that they

determine to be reasonable. A reduction in average speed subsequently leads to a reduction in road traffic accidents (Finch et al. 1994, Taylor et al. 2002), Taylor et al. (2000) produced a model to predict accident frequencies given the proportion of drivers exceeding the speed limit and the average speed, finding that excess speed and a higher speed limit were both associated with a higher accident frequency. Particularly, the risk of death at various speeds has been assessed in various studies, Richards & Cuerden (2009) found that at 60mph the risk of a driver dying in a head on collision between two cars is around 90%, but with a reduction in speed, this drops to around 50% at 48mph.

Taylor et al. (2000) demonstrated that traffic flow, link length, and the number of minor junctions all directly increased the number of accidents, while wider roads were associated with a reduction in the number of accidents. The *MASTER: Speed-accident relationship on European roads* (Baruya 1998), assessed road geometry and other features of rural roads in Europe, however road data for the United Kingdom was limited to a small area in the South East, suggesting that a comprehensive methodology for the extraction of UK rural road geometry is required for a more comprehensive study.

Newer developments like the Speed Limit Appraisal Tool mean that automated and quantitatively informed speed limits may be imposed on rural roads, however, this tool does not take into account key features such as road geometry, and simply builds on existing speed data and accidents (Department for Transport 2013b).

2.1.3. Accessibility

Rural accessibility can be defined in terms of economic and social opportunity as the proximity or ability for spatial interaction (Gutiérrez 2009). In relation to transport specifically, accessibility may be defined as the ability or opportunities by which basic services can be reached by either public or private transportation (Gutiérrez 2009).

Journey time on rural roads is often a primary concern when considering a reduction in speed limits, often higher speed is perceived to bring with it shorter travel times, and lower accessibility for people and goods (Department for Transport 2013a). Despite this, there is evidence to support that traffic travelling at constant, and lower speeds may result in overall more reliable journey times, and the time saved by travelling at faster speed is often overestimated (Stradling et al. 2008).

Transport accessibility for rural communities is far more limited than for urban communities, where often rural areas have limited or no public transport, meaning there is a heavy reliance on personal transport (Gray et al. 2001). Accessibility in this context therefore in turn limits social mobility, influencing social exclusion as there is a reliance on owning expensive personal transport to improve accessibility (Gutiérrez 2009).

Despite this, there has been little focus on the improvement of transport technologies in rural areas, with the potential for new technologies already implemented into urban areas to improve rural accessibility (Velaga et al. 2012). A key area to address is the level of accessibility towards hospital services for rural communities, where recent centralisation of these services has negatively impacted the level of access for rural communities (Mungall 2005). This also impacts the level of access for hospital services to reach rural areas, where distance and time taken to a hospital directly correlates with a patients mortality (Nicholl et al. 2007). Emergency vehicles are often larger than personal vehicles and as such it can be assumed that accessibility for these types of services is often more limited depending on the quality of rural roads.

Velaga et al. (2012) conducted a study outlining the key transport and technological challenges that limit accessibility within rural areas, demonstrating that the quality of rural infrastructure, and access to services are key factors driving social exclusion and limited access to goods and services. Velaga et al. (2012) suggest that technological innovations targeting rural areas may alleviate this problem through the production of user generated data, they note that certain challenges will come with this technology, notably their first point;

"Understanding basic technological infrastructure requirements in rural areas."

Suggesting a greater understanding of the existing rural road infrastructure is required before the introduction of existing urban technologies may improve access in rural areas.

2.2. LiDAR Data Classification

Aerial LiDAR classification typically follows two objectives, the classification of ground and non-ground points, and the classification of surface objects, including buildings, trees or roads (Charaniya et al. 2004). Classification takes two forms, *supervised* and *unsupervised*, supervised classification taking a *training* dataset, using it to estimate the parameters associated with the outcome hoping to be classified. These parameters are then used on unknown data, with a similar distribution to the training set, and used to classify features (Charaniya et al. 2004).

2.2.1. Digital Terrain Models

Early LiDAR classification primarily focused on the production of digital terrain models (DTM), Kraus & Pfeifer (1998) used an iterative linear prediction algorithm which used residuals to compute weights for each LiDAR point. Ground points produced residuals with negative weighting, and vegetation was more likely to produce residuals with higher weighting. From this 47.8% of points were classified as vegetation. Kraus & Pfeifer (1998) note that advances in the technology, such as the inclusion of multiple laser pulses would enable for a higher quality DTM.

Vosselman (2000), proposed a laser pulse filtering technique for distinguishing laser points that were reflected from buildings and vegetation, than those from ground, weights were assigned to points, determined by an assigned acceptable height difference between two neighbouring points. Limitations at the time of this study meant that processing required points to be aggregated into a grid for processing, resulting in significant information loss. Results were generally good for the simplicity of the method, giving a RMS error of 20-30cm, however Vosselman (2000) note that this error likely does not reflect the true precision of the DEM, which may be slightly worse.

The observation of height textures are another method for DEM extraction enabled through the use of LiDAR data. Maas (1999) used height variation between neighbouring LiDAR points to classify buildings, trees, and flat terrain, with enough detail to determine whether a building had a flat or sloped roof. Similarly Elberink & Maas (2000) noted that man made structures often have smooth, regular height textures, with small variations in height, while trees and other vegetation give an irregular height pattern, and used this to separate man made structures from vegetation. Empirical assessment of the accuracy of their technique resulted in a 98% accuracy for buildings, and 97% for trees, however ground based objects such as roads could only be detected with an accuracy of below 70% and Elberink & Maas (2000) suggest that multi-spectral data should be included to achieve better results.

Zhang et al. (2003) used morphological filtering of points assigned into a regular grid by inputting a minimum elevation for each cell in the grid, and interpolating the elevation of cells not containing any points. Accuracy of the results were assessed both quantitatively and qualitatively, giving 3% error from misclassified points, however qualitative observation of the DEM showed artefacts, primarily from larger buildings.

This paper will utilise a recent method for DEM production in order to classify ground and non ground points for subsequent road classification. The method chosen was proposed by Zhang et al. (2016) using *cloth simulation* to generate a DTM from LiDAR data. This algorithm, unlike other filtering algorithms, allows for a simplistic input, without the need for numerous parameters to ensure an accurate DTM. This method consists

of four main steps:

- *Initial State* A cloth is placed above the inverted LiDAR measurements.
- The displacement of each LiDAR point is calculated under the influence of gravity, meaning some points appear below ground measurements.
- *Intersection check*. For any points detected as being under the ground, they are moved to ground level and set to be unmovable.
- *Considering internal forces*. Movable points are moved according to neighbouring points.

Quantitative accuracy of this methodology gave results similar to top existing DTM production algorithms, but with a far more simplistic implementation.

2.2.2. Feature Classification

Developments in LiDAR enabled the possibility of classification by using laser intensity information and multiple returns, features of more advanced LiDAR systems. The TopEye system used by Axelsson (1999) allowed for classification of buildings and electrical power-lines using reflectance to obtain radiometric information about the area and note that this can be used to separate paved area from grassland. Power lines in particular benefited from the multiple returns produced by the LiDAR system used as they often gave one return from the power line, and one from ground.

Vegetation in particular exhibits multiple returns, whereas most man made surface objects do not, by considering the number of returns and homogeneous height variation Hui et al. (2008) were able to categorise surface vegetation into both high vegetation, low vegetation and smooth man made surfaces.

2.3. Road Classification

In comparison the extraction of vegetation and buildings from LiDAR, the extraction of roads poses far more of a challenge, due to there being less prominent height differences (Vosselman & Zhou 2009). Road classification is essentially a data clustering method to categorise data into road and non-road points, enabled through discovering patterns and relationship between variables and validation of findings (Saeedi et al. 2009). Clustering may be achieved through various algorithms, categorised generally into partitioning methods, hierarchical methods, density-based methods, grid-based methods, and model-based methods (Saeedi et al. 2009). Yadav et al. (2018) note that the periodic assessment of roads is greatly important due to the increasing traffic load, and new automated techniques will enable this in areas where in the past it had not been feasible. Due to the heterogeneous nature of certain roads types, the road environment is often complex, meaning collection and accurate processing of road features is challenging (Yadav et al. 2018).

Road classification methodologies have historically used purely aerial imagery, providing only road pixels and 2D location information (Yadav et al. 2018). Ferchichi & Shengrui Wang (2005) used high resolution satellite imagery for road centreline extraction from a suburban area based on cluster coverage. They used image segmentation through maximum likelihood to assign pixels to road and non-road classes, making the assumption that both classes gave a Gaussian distribution. Features for classification include the angular second-movement, contrast, and entropy of the image, based off image texture analysis by Dubes & Ohanian (1992). Results of the classification gave significant noise, noted as a possibility due to non conformance with a Gaussian distribution, however, centreline extraction from the resultant classification removed any pixels with low density and a K-means clustering algorithm was ran iteratively to determine road clusters. Wan et al. (2007) produced an automated method for mapping urban and suburban roads using high resolution satellite imagery, using spectral, context, shape and the structural features of roads. Using fuzzy segmentation,

classification of buildings, parking areas, and road clusters were obtained, but with large levels of noise. Angular texture analysis was able to reduce this noise, however large areas of incorrectly classified roads appear present in results. Additionally, while not mentioned in this study, the method proposed fails to address the differentiation between road and pavement, a key issue with the use of 2D imagery.

2.3.1. LiDAR Road Classification

The more accurate intensity data, and inclusion of multiple returns in LiDAR data enabled methods for categorising roads, and differentiating them from the surrounding ground, despite the similar elevation.

The majority of current road classification techniques using LiDAR have focused on unsupervised classification, often with the goal in vehicle automation using mobile LiDAR data (e.g. [Yadav et al. 2018](#), [Kumar et al. 2013](#), [Smadja et al. 2010](#), [Jaakkola et al. 2008](#)). Applications using aerial LiDAR have also followed this trend for unsupervised classification. [Clode et al. \(2004\)](#) used a sequential Hough filtering transformation to classify roads using aerial LiDAR data, achieved by first taking only the last pulse LiDAR coordinates, considered a digital surface model (DSM)¹. To obtain a DTM from the DSM, [Clode et al. \(2004\)](#) used a method as proposed in [Rottensteiner et al. \(2003\)](#), using a square structural element and grey scale opening to filter non-terrain objects. [Clode et al. \(2004\)](#) note that at the time of production, intensity data with LiDAR had been often subject to large amounts of noise, and their use of intensity values for road detection was only a recent possibility. Road classification was subsequently achieved through both intensity and height filtering. Minimum and maximum intensity values for the road surface type (bitumen) were used to remove points that fell outside these values, and points that were outside a selected tolerance from the DTM were also removed. This methodology achieved a completeness of 86%, correctness of 69% and quality of 65%, quantified by the use of a ground truth model. This methodology provides a simplistic method for unsupervised road classification that reached similar levels of accuracy as more complex methods for the time, at the expense of certain assumptions, namely the road surface material.

Many subsequent methods for road classification from LiDAR follow similar patterns, first identification of ground points through height data, and DTM extraction through interpolation, and following classification based on the attributes of the point cloud ([Vosselman 2009](#)). Due to the 3D information provided by LiDAR data, kerbs can be segmented from roads, achieving a more accurate road edge location when kerbs are present. However, due to the often small jump between kerb and road, this methodology is limited to new terrestrial mobile LiDAR data collection. [Jaakkola et al. \(2008\)](#) produced a methodology using mobile LiDAR data to classify road edges by segmenting kerbstones based on the height gradient along the scanned profile, with a final completeness of 73.9%, and correctness of 85.6%. Additionally, road markings were segmented from the road surface using intensity information. The mobile data collection for this study obtained a point resolution of between 10cm² and 100cm², with driving speeds of 20km/h to 50km/h. [Jaakkola et al. \(2008\)](#) note that due to the size of the data produced through this method, computation times were lengthy. [Yoon & Crane \(2009\)](#) similarly developed an approach for urban drivable terrain detection for automated vehicles through mobile LiDAR data, road edges were obtained through the slope and standard deviation of the height of points, finding the standard deviation to be far more efficient for edge detection. They note that while results were promising, it would take a very long time to collect data for a large number of roads, and at higher vehicle speeds, LiDAR points density is reduced below a usable threshold.

Other road classification techniques rely on the detection of planar or smooth surfaces at ground level, indicative of man made objects, which unlike vegetation, do not display sharp variation in height values ([Vosselman et al. 2004](#), [Darmawati 2008](#)).

¹Containing all surface objects, including ground points, vegetation, and man made structures such as buildings and roads.

2.3.2. Supervised Methods

Few supervised methodologies exist for LiDAR road extraction, Guan et al. (2013) used both aerial imagery and LiDAR data in combination with a training dataset to classify urban roads. The training dataset gave human labelled features, and used to train a maximum likelihood classification model. Matkan et al. (2014) extracted roads from LiDAR using a Support-vector Machine (SVM) classification. Again, training samples enabled classification into roads, trees, buildings, grassland and cement. Accuracy was determined through testing on three known road datasets, giving 63% to 66% accuracy. Ferraz et al. (2016) used supervised random forest classification to detect large-scale forest roads using LiDAR. They note particularly that given the scale of these roads, the efficiency of road extraction is most important, managing to achieve 80% accuracy with individual roads processed at 2 minutes per kilometer. Despite being forest roads however, the canopy was often not obscuring roads due to their reasonably wide surface, and as such this method produced inaccuracies in areas where the canopy was dense and covering the detected road. Charaniya et al. (2004) trained a mixture of Gaussian models using key features of both LiDAR and aerial imagery data. They found that for classification of buildings and roads, the key features of LiDAR that enable extraction were the height, intensity, and the number of returns, in addition to luminescence information obtained from the aerial imagery. Results gave an accuracy of 66%-84%.

Hatger (2002) used a combination of 0.5m resolution LiDAR data to extract the properties of roads given a database of known road centreline locations using a simplification algorithm. Properties included, height variation, curvature, and width. This paper used only LiDAR height information for road extraction and so produced a large amount of noise. To combat this, a RANSAC algorithm was used to determine the most likely position of the straight line road edges.

Elberink & Maas (2000) produced an automated method for modelling highway infrastructure using air-borne LiDAR, 2D topographic information, and a database of known road locations. True road polygons were extracted using a seed-growing algorithm, and hough transformation.

These supervised techniques give insight into the feasibility for rural road extraction, given a dataset of known road centrelines. With improvements to the quality of LiDAR data more recently, a methodology for road feature extraction using road centrelines and LiDAR may more comprehensively include features that distinguish LiDAR from surrounding objects, including intensity, the number of returns, and aerial luminescence.

2.3.3. Rural Road Extraction

Many recent road extraction techniques have relied on kerb extraction or the detection of buildings, features uncommon to rural roads in the UK, where non road surfaces often include managed grass verges, with little height difference in comparison to roads (Kumar et al. 2013). Rural classification therefore must rely on alternative features of roads, notably the difference in intensity produced by vegetation, explored in various studies (e.g. Vosselman 2000). Additionally, overhanging tree canopies are uncommon features of roads that have been previously classified, and as such, a methodology for classifying rural British roads must take this limitation into particular consideration.

2.4. Overview of this Paper

Finally, outlining the key features that may be considered when determining road quality will help to inform the methodology for road feature extraction in this study. These are:

- **Width:** Narrower roads are associated with an increased number of accidents in many studies of rural

roads (Taylor et al. 2002, Aarts & van Schagen 2006, Taylor et al. 2000)

- **Surface quality:** Poor quality road surfaces have been shown to increase the number of road traffic accidents (Fleming et al. 2009)
- **Blind corners/winding roads:** Blind corners increase the risk of accidents, and higher speeds mean stopping distances are often above the distance visible around rural road corners in the UK. Blind corners are particularly an issue due to the tall hedgerows that often bank rural roads (Aarts & van Schagen 2006, Wu et al. 2013)
- **Road Steepness:** Steeper roads have an increased skid risk, and their quality is more likely to deteriorate (Moore et al. 2006, Viner et al. 2004)

Computation time is considered in this study to be a core concept for consideration, noted in (Zhang et al. 2016) as a key limitation of particular classification techniques, and is often not specified. The data processing and analysis throughout this paper considers optimisation of code to be of particular interest, and aims to produce results that match more complex methods, but taking a more simplistic, and less computationally intensive methodology. While the focus of this study is primarily on the methodology, the discussion will outline in particular the applications of this approach to road feature extraction, addressing the broad issues that are inherent due to the lack of quantitative information regarding the majority of the road network in the UK.

3. Methodology

THIS paper primarily makes use of the free open source statistical language **R** ([R Core Team 2019](#)). Managing the large LiDAR datasets from my personal computer was made possible through the `lidR` **R** package ([Roussel & Auty 2019](#)). Further details regarding the **R** environment and computer setup used for this paper is given in [Appendix A](#). All content was written using \LaTeX combined with the `rnoweb` file type ([Ihaka 2011](#)), for *Literate Programming*¹. The template is built from scratch but takes much inspiration (and code) from the R-LaTeX-Template.

All code is hosted on my personal [GitHub account](#), along with my complete dotfiles, used in conjunction with the Linux distribution Manjaro, and the i3 window manager. All writing and code was produced using [Neovim](#) with my personal configuration to implement integrated development environment (IDE) style features for writing R code, while also providing essential features for writing in \LaTeX . Neovim has the benefit of being both highly customisable, and lightweight, which allows for much lower system utilisation compared with R Studio when working with large datasets. One essential Vim plugin to mention is [Nvim-R](#), providing an **R** REPL connection to vim, and other useful functions.

Given in [Appendix A](#) are the code snippets utilised in this methodology, for many equations, the relevant code is given as a reference to the appendix location, in the form **A.x.x**.

3.1. Data

LiDAR point cloud data was downloaded through the UK Government's open data repository which uses the [Open Government Licence](#), allowing for:

- Copying, publishing, distributing and transmission of the data
- Adaptation of the data
- Commercial and Non-commercial use of the information

LiDAR data used in this paper is available [HERE](#) under this licence ([UK Government 2019a](#)). This data was given as a compressed LAS file format (.laz), the **R** package `lidR` provided the function `catalog()` which enabled each separate .laz to be combined into one object of class `LAScatalog`. Analysis on this object could then be split into chunks (selected as 500m²), allowing for multi-core threading to speed up analysis, and a reduction in the memory overhead when reading in data, often a limitation of the **R** language as objects are stored entirely into memory when read ([Wickham 2014](#)). The `LAScatalog` object did not require the compressed .laz files to be read into memory as .las files, meaning memory limitations were far less of a problem.

Aerial imagery was downloaded through [Digimap®](#) which uses the *Aerial Digimap Educational User Licence*, allowing for free use of the data for educational purposes ([The University of Edinburgh 2019](#)).

¹See [Knuth \(1984\)](#); "Let us change our traditional attitude to the construction of programs: Instead of imagining that our main task is to instruct a computer what to do, let us concentrate rather on explaining to human beings what we want a computer to do."

Road centreline geometries were accessed through the [Ordnance Survey Open Data repository](#) which shares the Open Government licence. These were downloaded in the GeoPackage format (.gpkg) nationally and cropped to the extent of the LiDAR point cloud data.

3.2. LiDAR Preprocessing

The total number of LiDAR points used in this study is 9,419,272. All LIDAR data has a vertical accuracy of +/-15cm Root mean square error (RMSE). An overview of the LiDAR data selected for this study is given on Table 3.1. The variables of primary interest are:

- **z:** The distance a laser pulse is reflected back to scanner, calculated by the time taken for a return pulse to be detected.
- **Intensity:** The amplitude of the return pulse, reflected back by the surface terrain or objects.
- **ReturnNumber:** A number of range 1-5, indicating for a point, the corresponding order of a reflected laser pulse. A ReturnNumber of 1 indicates the first return for a pulse (and highest z value), a return number of 5 indicates the last return (and lowest z value).
- **NumberOfReturns:** The number of return pulses for a single laser pulse (maximum of 5).
- **Classification:** A number given to a point indicating a specific numeric classification. Of interest in this study is a classification of 2, indicating a ground point. More information can be found [here \(ESRI 2019\)](#), which outlines numerical classifications for various vegetation types and man made structures.

3.2.1. Last Pulse

The LiDAR point cloud data used in this paper gives the values for 5 pulse returns. The canopy above roads may be excluded through ignoring early pulses (higher Z values), therefore only the last pulse values for any point are selected, this can be expressed as;

$$\mathbf{p}_i = (lpx, lpy, lpz, lpi),$$

A.2.5

where \mathbf{p}_i is a single instance of a LiDAR point within the chosen point cloud, lpx is the last pulse x coordinate, lpy the last pulse y coordinate, lpz the last pulse z coordinate, and lpi the last pulse intensity value.

3.2.2. Normalisation

Ground points were classified using the Cloth Simulation Filtering (CSF) algorithm, as described in [Zhang et al. \(2016\)](#). Points were already classified in the data provided, however, as the classification technique was unknown, reclassification was considered necessary. The general implementation simulates the movements of a piece of cloth lying over the inverse of a point cloud, as the point cloud is flipped, the cloth settles beneath ground points, while covering points that lie separate to the ground, essentially forming a digital terrain model (DTM), cloth simulations are described in more detail in [Bridson et al. \(2005\)](#) and subsection 2.2.1. The CSF algorithm is given;

$$X(t + \Delta t) = 2X(t) - X(t - \Delta t) + \frac{G}{m} \Delta t^2,$$

A.2.5

Table 3.1: LiDAR Point Cloud Summary Data

	Mean	SD	Min	Max
Z	80.58	5.97	64.85	115.79
Intensity	177.10	124.85	1.00	4064.00
ReturnNumber	1.47	0.95	1.00	5.00
NumberOfReturns	1.94	1.42	1.00	5.00
ScanDirectionFlag	0.50	0.50	0.00	1.00
EdgeOfFlightline	0.00	0.03	0.00	1.00
Classification	3.04	1.70	1.00	8.00
ScanAngleRank	-2.01	13.16	-22.00	22.00

where m is the mass of a single LiDAR point (set to 1), Δt is the time step between points and G represents the gravity constant. The implementation of this algorithm was given as part of the `lidR` package.

With the classification of ground points, (given *Classification* = 2), a full DTM may be produced through spatial interpolation of the classified points. This process is called normalisation, and ensures that when extracting height information, any observed values are due to objects on the surface of the terrain, and not due to the lie of the terrain itself. Interpolation uses the inverse distance weighting and k nearest neighbours algorithms to produce the DTM. Nearest neighbours were selected as $k = 10$, with $q = 2$ for the inverse weighting, and used to produce a DTM with a resolution of 1m. This particular technique was selected over more comprehensive methods such as kriging as the number of points is very high, and the small benefit was considered minimal compared with the increase in computational load. The z values from the DTM were then subtracted from the LiDAR point cloud, leaving a normalised point cloud.

3.2.3. Points Extent

With the normalised last pulse point cloud, the point cloud was clipped to within a 30m extent of each known road location, using the OS road shapefiles. Selecting a 30m extent ensured that even with slight inaccuracy in road location, the road LiDAR points would likely not be excluded. A large number of unimportant points were therefore removed, saving on computational resources. Additionally this extent ensured that both road and non road points were included, but reduced the chance of false positives from occurring as fewer non road points were now included in the analysis.

A.2.6

3.2.4. Noise Filtering

Intensity noise was filtered through area based outlier detection, measuring the 95th percentile values within a 10m by 10m area, removing all points above the 95% percentile. Expressed;

$$\mathbf{c}_i = \left(\mathbf{p}_i \in \left[\frac{95}{100} \times \mathbf{p}_{i_{lpi}} \right] \right)$$

$$A(\mathbf{c}_i) = 10m^2$$

A.2.4

where \mathbf{c}_i represents a $10m^2$ selection of LiDAR points, where each point (\mathbf{p}_i) has an intensity value within the 95% percentile intensity for all points ($\mathbf{p}_{i_{lpi}}$) within \mathbf{c}_i .

3.2.5. LiDAR Catalog

As mentioned above, objects of class LiDAR catalog enabled more efficient processing through allowing the LiDAR point cloud to be processed in predefined batch sizes. Considering a collection of processed LiDAR points, with last pulse, normalised, clipped to 30m road extents, and intensity noise filtered, points were grouped into $500m^2$ areas;

$$\mathbf{C}_i = \{\mathbf{c}_1, \mathbf{c}_2, \dots, \mathbf{c}_N\}$$

$$A(\mathbf{C}_i) = 500m^2$$

A.2.4

And each $500m^2$ area collectively represents the overall processed point cloud;

$$\mathbf{S} = \{\mathbf{C}_1, \mathbf{C}_2, \dots, \mathbf{C}_N\}$$

A.2.10

3.3. Road Analysis

This section combines data extracted through the OS road shapefiles, preprocessed LiDAR data, and aerial imagery to obtain a set of criteria to assess the chosen road network. These criteria are;

- Road Width
- Bend Sharpness
- Road Steepness
- Surface Quality

The roads in this paper consist of these functions;

- B Road
- Minor Road
- Restricted Local Access Road
- Secondary Access Road
- Local Road

with B roads considered classified roads, and other functions considered unclassified. All roads are single carriageway, and so for the purpose of this analysis it is assumed they likely have the default national speed limit of 60mph. Individual road identification was difficult, as most roads were not given a name or identifier, in an attempt to solve this issue, each individual linestring as provided by the OS road centreline data was considered to be a road, with each given a unique road identifier (Road ID). Figure 1.1 outlines what is considered to be a road in this analysis. All private roads were removed, as were roads below 50m, often those clipped by the extent of the LiDAR data. As many roads did not have a name to be identified by, a column called `road_id` was produced, corresponding to a line segment between two junctions (not necessarily a full named road).

Table 3.2: OS Roads Data Summary

Example	
id	idE381337E-E88D-4232-8CAD-F543F178EBE4
endNode	id42B6F387-D838-445C-AA7A-6558362B7B9F
startNode	idC8EE8B4C-D965-436A-BA02-A0925A6EA1B8
roadNumberTOID	osgb4000000013398492
roadNameTOID	
fictitious	FALSE
roadClassification	B Road
roadFunction	B Road
formOfWay	Single Carriageway
length	241
loop	FALSE
primaryRoute	FALSE
trunkRoad	FALSE
roadClassificationNumber	B5392
name1	
name2	
roadStructure	

3.3.1. Road Sampling

The LiDAR point cloud data was sampled at regular 10 meter intervals for each road, perpendicular to the road direction, ensuring that when road direction changed, the sampling locations remained perpendicular. Each road was first split into nodes at which road direction changed, and from this, points at 10 meter intervals between two connected nodes were calculated;

$$p_k = p_1 + |p_2 - p_1| \times I_k$$

where p_k is a calculated point long a line, I_k is the interval value which increases by 10 meters until the length of the total distance of the node, given $I_1, I_2, \dots, I_k > 0$ and $k \geq 2$.

$$I_k = (L_k + 10) - T_k$$

$$L_1 = 10$$

$$T_k = T_{k-1} + E$$

A.2.11

where L_k is the distance from the start of the node to the current sample line position, T_k is total length of all nodes within a road from the start of the road and E is the euclidean distance between two nodes.

To calculate the sample locations, perpendicular to the roads, first the x and y euclidean distances from a reference point p_k and the end of the current node n_{k+1} were calculated;

$$\begin{aligned} len &= \sqrt{(n_{k+1} - p_k)} \\ p_i &= (30/len) \times (n_{k+1} - p_k) \end{aligned}$$

A.2.9

from this, the lengths were inverted, giving two points (p_i) of distance 30 from p_k . Inversion was achieved by subtracting the given len_n x value from p_k , while adding the len_n y value, and vice versa. These perpendicular sample lines were buffered to a width of 2m, giving a total area of 120m^2 per sample. These were spatially joined to the existing LiDAR point cloud data, removing any points that fell outside the sample lines.

3.3.2. Aerial Imagery

With the perpendicular sample lines extracted for the length of every road, to assist with the prediction of correct road locations, true colour aerial imagery was included. This imagery was first converted from three band RGB raster images, to a single-band grey-scale raster brick with values ranging 0 to 255, considered to be luminescence information.

$$\text{luminescence} = \frac{\text{Band}_1 + \text{Band}_2 + \text{Band}_3}{3}$$

3.4. Linear Probability Models and Road Width

To classify road and non-road, linear models were constructed and compared to assess effectiveness. A maximal approach was chosen, selecting all appropriate predictor variables, iterating through models by removing variables that did not significantly influence the model outcome, or created noise.

An additional variable *Dist* was created and included, representing the shortest distance from a point to the centreline of the road it is associated with, considering that road points should be weighted more towards points that are closer to the centre-point of the road.

Linear probability models essentially follow the same formula as a linear regression model:

$$Y_i = \beta_0 + \beta_1 + X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki} + u_i$$

but given a binary outcome variable Y_i , this is considered to be a linear probability model, taking the form;

$$E(Y|X_1, X_2, \dots, X_k) = P(Y = 1|X_1, X_2, \dots, X_k)$$

Where;

$$P(Y = 1|X_1, X_2, \dots, X_k) = \beta_0 + \beta_1 + X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki}$$

β_j therefore may be interpreted as the change in the probability that $Y_i = 1$, with all other predictor variable constant. β_j may be estimated using Ordinary Least Squares regression (Hanck et al. 2019).

Likelihood values from the predictions gave a range of numerical values, points that fell below a certain threshold were removed, leaving only points that were most likely correctly identified as road points. This threshold was assessed qualitatively through both observation of the distribution of probability ranges for each model, and results gained through different thresholds. Considering a threshold x , this may be expressed as;

$$\mathbf{S} = \left(\mathbf{p}_i \in \left[\frac{x}{100} \times \mathbf{p}_{i_{lm}} \right] \right)$$

Where \mathbf{S} is the total point cloud.

Further qualitative assessment of the results revealed that some points considered to be noise were still present, but often isolated. To ensure no isolated points were present, the minimum distance between each

point, and the nearest neighbouring point was checked, if a single point was considered isolated, with over 1m between it and any other point, it was removed.

$$D = \sqrt{\delta x^2 + \delta y^2}$$

$$\mathbf{S} = (\mathbf{p}_i \in [D \leq 1])$$

A.2.15

given D is the minimum distance between a point and any other point.

\mathbf{S} now gave of a collection of predicted road points for each sample line along a road segment, with noise removed. To obtain road widths from these points, the maximum distance between two points in a particular sample was determined, these points were kept and all others removed. A linear section of road with two samples resembles Figure 3.1.

A.2.16

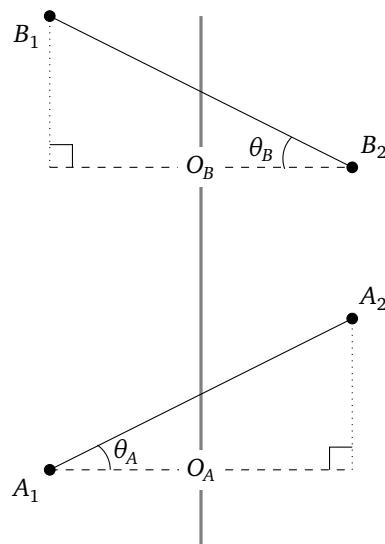


Fig. 3.1: Road LiDAR points at maximum distance apart for each sample location. Showing two example sample locations (A and B), road centreline represented by the thick grey line. True road width is indicated by the dashed lines O_A and O_B .

To determine the width of the road section, according to the final two selected points at every node, Pythagoras could be used to find the opposite line length (O_K), perpendicular to the road segment, considering the distance between the two points to be the hypotenuse ($|K_1 K_2|$) of a right angled triangle (Figure 3.1). The average width for each road identifier was then found.

$$O_K = |K_1 K_2| \times \cos(\theta_K)$$

A.2.20

3.4.1. Improved Road Centrelines

During the analysis of the linear models, it was noted that road centrelines were often inaccurate, giving road outcome values that were not representative of the road surface. In an attempt to adjust for this, road centrelines were adjusted based on the centre location of road points in each sample, classified through an initial linear probability model. The mid point between two points (x_1, y_1) and (x_2, y_2) can be expressed as;

$$\left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2} \right)$$

A.2.18

With the mid point of each classified road sample, these were than joined for form new centrelines, and a further linear probability model was ran and compared, to determine the effectiveness of this technique.

A.2.19

Given the improvement in road centreline locations, it was considered feasible to construct linear probability models individually for each sample location on each road. This technique would allow for per road variation in material type or quality, and potentially reduce the amount of noise brought in from inaccurate centrelines. Preliminary testing of this method revealed that it was essential to remove any sample containing tree canopy, as given the small number of points, the predictions were based off points that misrepresented true road points. Additionally, individual linear models allowed for some filtering through p values, which was not achievable through global linear models, given the very large number of points.

3.4.2. Final Model Analysis

// talk about lm beta coefficients here, limitations of p values nmaybe

To aid with model interpretability, the direct comparison between each variable in the analysis was enabled through centering and scaling through the use of beta coefficients [Peterson & Brown \(2005\)](#);

$$\beta_p = \frac{\text{Cov}(r_p, r_b)}{\text{Var}(r_b)}$$

3.5. Road Angles

The angle of bends in roads were identified through the nodes produced in the creation of the road shapefiles. First the road linestrings were split into points, with coordinates representing each node within a road, a point at which the orientation of the linestring is altered.

The bend in a road was considered to be the *bearing angle* θ , from a point $A(a_x, a_y)$ to a point $B(b_x, b_y)$, with the angle measured in a clockwise direction from north. This is represented on Figure 3.2.

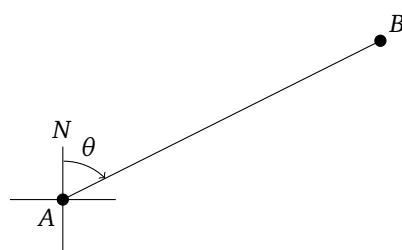


Fig. 3.2: Bearing Angle Between Road Segments

To find the angle θ , the point B can be represented into relation to point A as;

$$(b_x, b_y) = (a_x + r \sin \theta, a_y + r \cos \theta)$$

Where r is the length of the line segment AB . Rearranging the equation for θ gives;

$$\tan \theta = \frac{b_x - a_x}{b_y - a_y}$$

This equation can be rewritten to calculate the value of θ using the *atan2* function;

$$\hat{\theta} = \text{atan2}(b_1 - a_1, b_2 - a_2) \in [-\pi, \pi]$$

Finally the bearing angle $\theta \in [0, 2\pi]$ is given as;

$$\theta = \begin{cases} \hat{\theta}, & \hat{\theta} \geq 0 \\ 2\pi + \hat{\theta}, & \hat{\theta} < 0 \end{cases}$$

A.2.22

With the bearing angle of the first line segment AB for a particular road, the change in orientation of the second road segment BC may be given as $\theta_2 = \theta_1 - \theta_0$, with additional nodes following the pattern $\theta_k = \theta_{N(N+1)} - \theta_{(N-1)N}$.

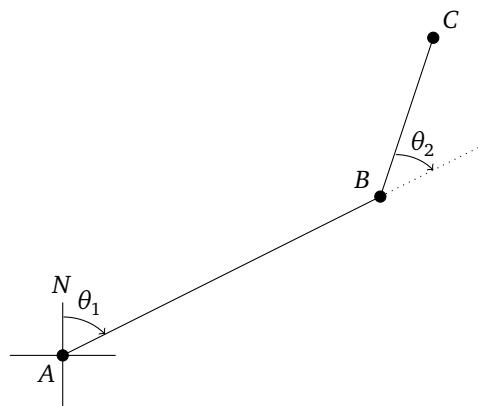


Fig. 3.3: Bearing Angle Between two Road Segments

For each road the, maximum bearing angle between two nodes was selected, as well as the average bearing angle for a certain road.

3.6. Road Node Elevation Change

The elevation change between two road node points was calculated by first selecting non-normalised LiDAR points at a geometric node within a $1m^2$ area. Nodes were obtained from the OS road data, as point coordinates obtained when the linestrings were split. LiDAR points were then filtered by those only classified as ground, and with only a single return, to reduce the likelihood of inaccurate z values from canopy or other vegetation and vehicles. The mean z value of points were found for each node, and elevation change between each node was calculated. For each road, the total elevation change per kilometer was calculated.

3.7. Surface Quality

Surface quality was assessed roughly through the range in intensity values found in each known road point, and the average number of returns for a road for sample lines not obstructed by canopy, indicated by single returns.

3.8. Estimate of True Widths

QGIS (QGIS Development Team 2019) used to measure roughly the width at various points along each road using 25cm resolution aerial imagery. With the widths, the results of each model was compared to assess model accuracy. Each width was normalised to allow comparison between each road, and to give a final average accuracy value. Normalisation was achieved through finding the relative difference in width as a percentage;

$$W_n = \frac{W}{W_e \times 100}$$

where W_n is the normalised width, W is the average width per road derived from the linear model, and W_e is the qualitatively estimated width. Given some widths occasionally were overestimated, to ensure the outcome of this calculation gave a relative value, any normalised width given a value above 100 was reassigned;

$$W_n = 100 - W_n$$

given $W_n > 100$.

3.9. Road Quality Assessment

To provide a method for direct comparison between each road, the extracted features are normalised and combined as one to produce the Road Quality Index (RQI).

Normalisation of each road feature was achieved through a simple range normalisation;

$$m \mapsto \frac{m - r_{\min}}{r_{\max} - r_{\min}}$$

Where r_{\min} denotes the minimum of the range of a variable, r_{\max} denotes the maximum of the range of a variable, and $m \in [r_{\min}, r_{\max}]$ denotes the variable to be scaled. As an increase in road width is associated with a higher quality road, as opposed to larger values of each other variable indicating a poorer quality road, the width values were first inversed before normalisation. An additional variable, reliability was presented in addition to the RQI, which gives a value for the number of points per road length, (P_n/L), allowing for some information regarding the density of sample points to be considered in analysis.

Following normalisation, the sum of all normalised variables for a particular road were taken, and subtracted from 1 to give positive values indicating better quality roads, and lower values indicating lower quality roads. The value obtained from this was called the Road Quality Index, presented in full on Table 4.3.

4. Results

RESULTS for the overall methodology are given in this chapter, covering the initial preprocessing of LiDAR and other data, and following onto the width extraction of roads, in addition to other geometric features. The primary goal is to critique the effectiveness of the proposed methodology, and provide a baseline for future improvements particularly in road classification and width extraction, while presenting the quantifiable results in a way that relates to the overall quality of each road. Outlined in detail therefore is sensitivity analysis of the road classification models, presenting both qualitative and quantitative assessments of accuracy. Assessment of the improvement to road centreline locations, before a detailed look at the final results of the analysis, demonstrating how road feature extraction may inform the overall quality of a road, comparing the extracted data to aerial imagery for a visual assessment of the results.

As noted in Section 2.4, computation time is considered an important aspect of this analysis. The total time taken, including all data preprocessing, perpendicular sample line extraction, LiDAR sample extraction, construction of linear models, reprocessing of road centrelines, road feature extraction, and further analysis is 15.45 minutes.

4.1. Data Preprocessing

Table 3.1 indicates that there are likely some points with noise, particularly reflected by the highest intensity value (4064) relative to the mean value (177). As noted in previous LiDAR classification methods, intensity is often subject to noise, therefore a simplistic noise exclusion technique was considered, as described in section 3.2.4, presented by [Roussel & Auty \(2019\)](#).

Following intensity noise filtering, the highest intensity value was now 746, with a mean of 182. Figure 4.1 (A) gives the distribution of Intensity values for all points within the study area, showing two clear spikes in intensity, at a value of around 50, with another around 350. This is reflected similarly in the Luminescence values, with two peaks at around 50 and 120 (Figure 4.1 (B)).

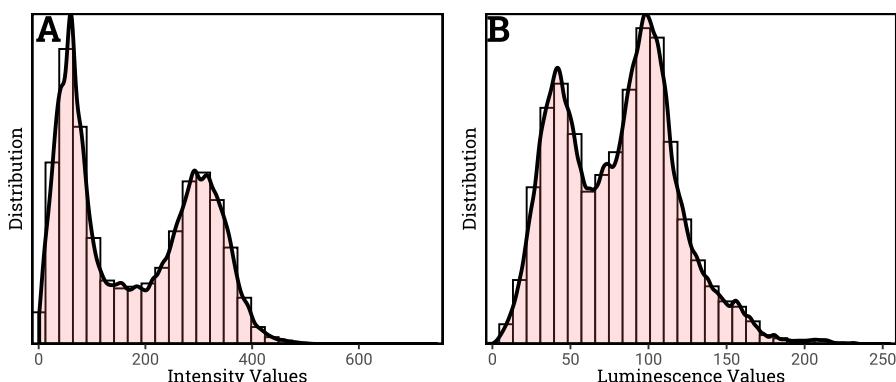


Fig. 4.1: Post noise filtering LiDAR point cloud distribution of; (A) Intensity, and (B) Luminescence

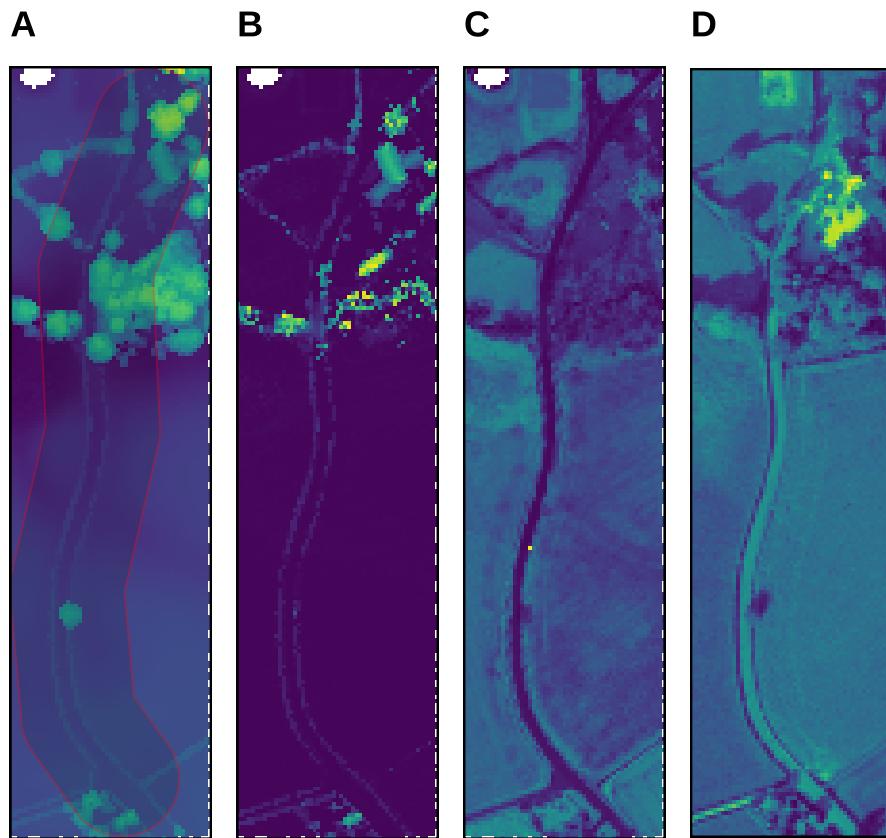


Fig. 4.2: LiDAR point clouds for one selected road section aggregated into $2m^2$ grids, (A) Base point cloud z values, road location indicated with a 30m buffer (B) Normalised Point cloud z values for only last returns (lpz) (C) Normalised Point cloud Intensity values for last returns, (D) Aerial Data combined to 1 band

Figure 4.2 gives the results of further LiDAR preprocessing, comparing Figure 4.2 (A) and Figure 4.2 (B), shows how last pulse LiDAR filtering allows for the removal of the majority of tree canopies, leaving only ground points that are considered hard surfaces, and as such are the lowest point the laser pulse has penetrated. Additionally, Figure 4.2 (B) shows how a digital terrain model, created through interpolation techniques, using only the base point cloud may be used to normalise the points, giving a digital surface model which only shows the true height of surface objects, without having to consider the variation in lie of the land. However, Figure 4.2 (C) indicates that while filtering for last pulse returns may appear to remove much of the canopy, reflected in the z values, the intensity values for points that have penetrated the canopy are lower than those that did not (See the tree just below the centre of the road section). This particularly creates issues in the distinction between road and non road in neighbouring areas where the intensity "shadow" created removes the distinct difference in intensity. This suggests that for ground points with multiple returns, the intensity values are likely far less reliable for road classification. Quantitative analysis of this limitation reveals that for ground classified points with a single return the average intensity value is 214.9, while for ground classified points with multiple returns, the average intensity value is 88.15.

4.2. Perpendicular Sampling

Unlike previous road classification methodologies, this paper aims to focus primarily on road feature extraction, and not the accurate extraction of road locations, as road centerline locations provided by Ordnance Survey already exists. Due to this, a sampling methodology was considered for several reasons; sampling the

LiDAR point cloud gives a significant reduction in the number of points that need to be processed. Using the 30m buffer from known road locations, and sample line extraction, the number of points from the original LiDAR point cloud for the 1km² area was reduced from 9,419,272 to 616,015 giving a reduction in number of points by 93.46%. Additionally, including sample lines allowed for filtering based on features of each sample, allowing for samples fully obscured by canopy to be identified through the number of returns, and excluded easily if required. See Figure B.1 for an overview of all the sample lines produced in this analysis.

4.3. Linear Probability Model Sensitivity Analysis

Selected based on literature, and correlation analysis of the variables (Table ??), the first model was constructed to include all variables of importance from the LiDAR point cloud, z , Intensity, and Number of Returns. Additionally, luminescence from aerial imagery was included, and the minimum distance of a point from the known road centreline location.

This first (maximal) model was constructed as;

$$\begin{aligned} \text{Road}_t = & \alpha + \beta_1 \text{Intensity}_t \\ & + \beta_2 \text{Luminescence}_t \\ & + \beta_3 Z_t \\ & + \beta_4 \text{NumberOfReturns}_t \\ & + \beta_5 \text{Dist}_t + \epsilon \end{aligned} \quad (4.1)$$

As proposed in Chapter 3, the road outcome variable was given as points that fell within a 2m buffer of the known road centreline locations. As such, this meant that a fair number of false negative points are expected to have occurred, where points outside 2m of a road centreline location would be incorrectly classified as non-road. Due to this, the classification of non-road and road was not a simple selection of points that were above a 50% threshold prediction as being road. To determine an appropriate cutoff for road predictions a

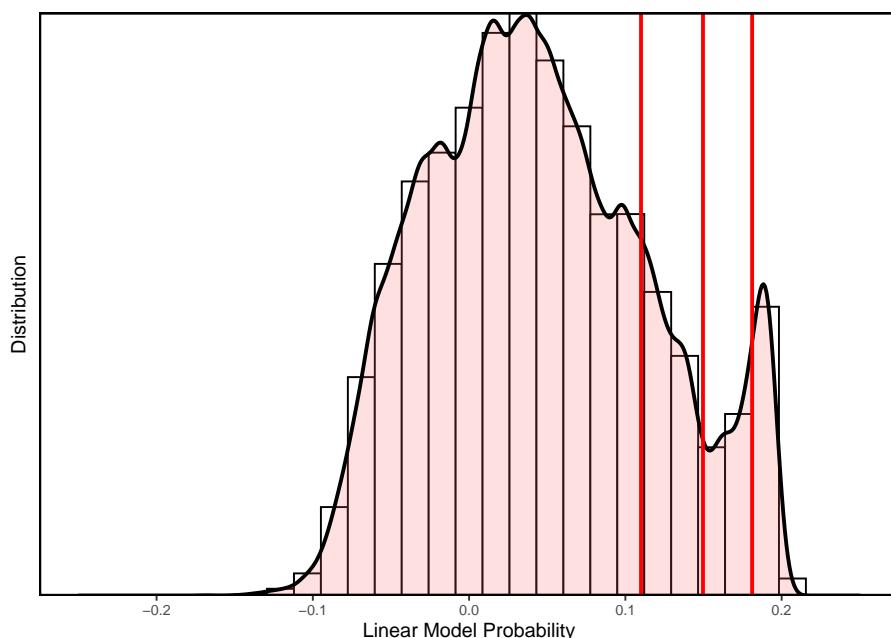


Fig. 4.3: Linear Model Probability Distributions for the Maximal Model, showing vertical lines at the 95th, 90th, and 80th quantile of the distribution

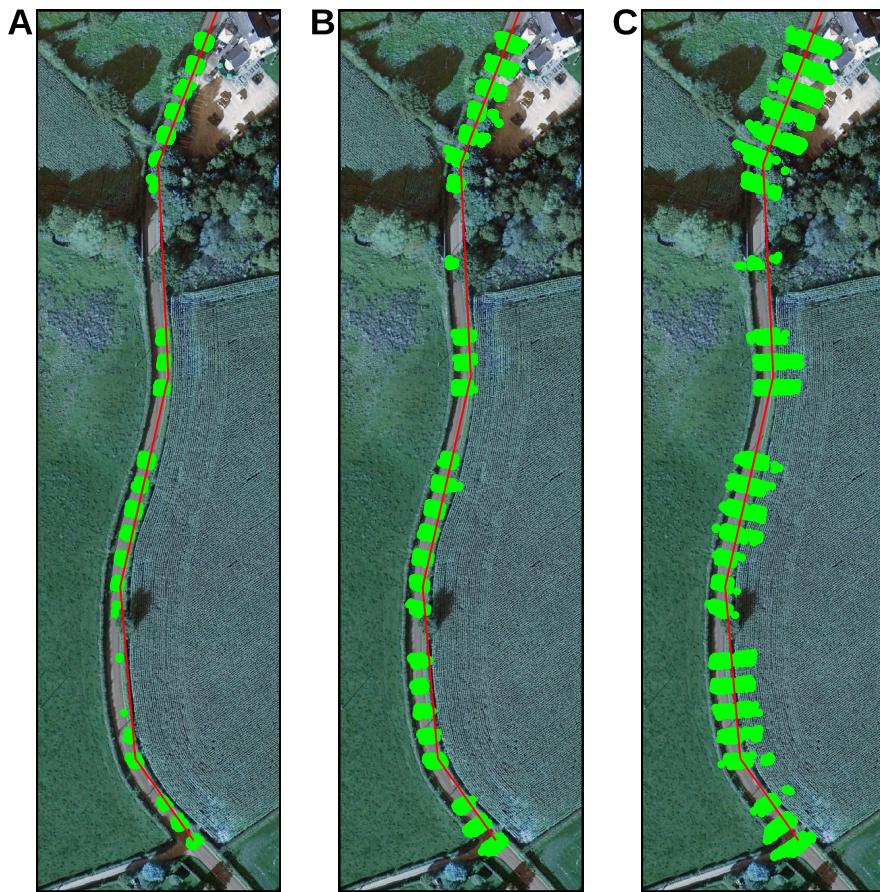


Fig. 4.4: Comparison between Linear Prediction Quantiles; (A) 95th Quantile, (B) 90th Quantile, (C) 80th Quantile

histogram was produced which gave insight into the distribution of the linear prediction values (Figure 4.3).

Figure 4.3 shows that there is a clear separation between the majority of points, and higher probability values. This therefore gives insight into the true divide between true road and non-road points, allowing for a qualitative analysis to select the most appropriate quantile of probability values. Three quantiles were chosen, the 95th, 90th and 80th, as indicated on Figure 4.3.

Figure 4.4 reveals that qualitatively, the optimal choice for a quantile filtering of the linear probability distribution is likely the 95th quantile (Figure 4.4 (A)). However, observation of the southern section of Figure 4.4 (A) reveals that inaccurate centreline locations have led to an incomplete linear model analysis. To compensate for this, a further method proposed aims to improve the accuracy of the given road centreline locations. Additionally, Figure 4.3 reveals that for the 95th quantile probability values, shadow from road hedgerows appears to reduce the model accuracy, as noticeable towards the top end of the road. For this reason, a second model was constructed for later comparison, which removes the *luminescence* information provided by the aerial imagery.

$$\begin{aligned} \text{Road}_t = & \alpha + \beta_1 \text{Intensity}_t \\ & + \beta_2 Z_t \\ & + \beta_3 \text{NumberOfReturns}_t \\ & + \beta_4 \text{Dist}_t + \epsilon \end{aligned} \quad (4.2)$$

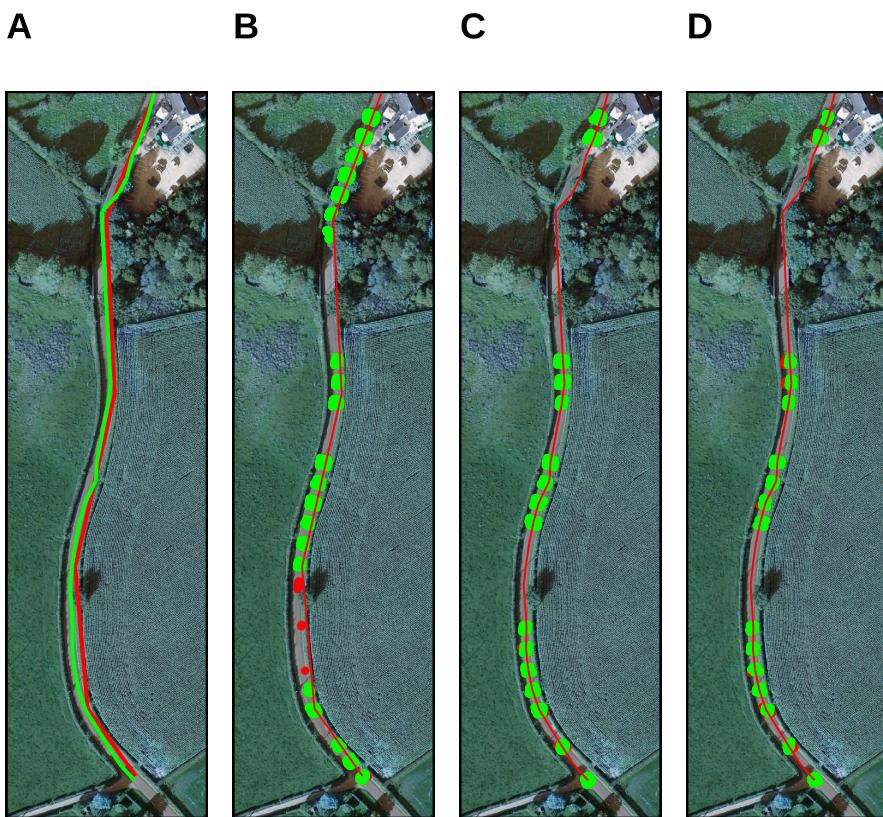


Fig. 4.5: Comparison between Linear Probability models applied to; (A) OS Road Centrelines, and (B) Derived Centrelines. Green points give classified road locations, red show classified road locations removed through isolation based filtering

4.4. Corrected Centreline Extraction

To improve road centreline location accuracy, the 90th quantile results from the first linear probability analysis were used, due to there being a more complete selection of points, but without compromising the true location of roads by including too many outside points.

New road centrelines are given on Figure 4.5 (A), particular improvements are given where the road curves between two open fields, but the original centreline was given as a straight line, covering the hedgerow, and no road surface.

Qualitative comparison between the Linear Probability Model based off the original centreline locations reveals an improvement in overall road detection, particularly towards the edge of roads, while additional samples are achieved in areas which previously had no coverage due to the incorrect centreline placement (Figure 4.5 (A)). However, it appears that in areas where there are higher levels of linear predictive inaccuracy, the new centrelines are less accurate, thankfully, noise exclusion techniques employed have removed samples that fall within these areas, particularly noticeable at the northern end of Figure 4.5 (C). Figure 4.5 also gives information regarding distance based noise exclusion technique, which has allowed for the exclusion of isolated points accurately on Figure 4.5 (B). Improved centreline locations allowed for individual linear models (Figure 4.5 (D)), while it was assumed that individual linear models would potentially produce more accurate width estimations, it is hard to differentiate between the global and individual linear models (Figure 4.5 (C) and (D)).

Table 4.1: Model Coefficients, Comparison between Linear Probability Model 1 and 2

Variable	LM 1	LM 2
Intensity	-0.30	-0.30
dists	-0.33	-0.33
Z	-0.07	-0.07
NumberOfReturns	-0.22	-0.22
lum	0.01	

Table 4.2: Comparison between different linear probability models for each individual road, in relation to estimated true road width

ID	Class	LM <i>i</i>	LM 1	LM 2	LM 0
20	Local Road	91.04	84.95	72.05	58.86
30	Minor Road	87.48	78.25	90.22	50.53
36	Minor Road	87.43	79.20	85.97	90.87
10	Minor Road	83.55	96.37	95.77	61.43
9	Minor Road	82.76	70.92	81.73	80.13
12	Minor Road	82.74	88.24	89.02	67.28
7	B Road	76.50	59.95	61.13	76.61
8	Minor Road	75.71	73.61	74.95	85.43
4	Minor Road	73.77	87.62	84.58	61.90
33	Minor Road	71.40	67.01	69.11	61.29
1	B Road	67.86	66.55	70.47	64.10
34	Minor Road	67.31	81.14	80.26	75.91
6	Minor Road	64.93	81.88	75.97	80.59
15	B Road	61.63	91.10	86.31	76.50
16	B Road	61.23	40.34	59.83	42.91
31	Minor Road	60.75	61.11	63.96	70.55
18	Minor Road	59.53	73.73	58.16	71.71
13	B Road	53.62	53.66	52.34	51.97
14	Local Road	53.60	56.81	64.28	98.88
21	B Road	48.68	51.08	50.51	38.17
Means:		70.58	72.18	73.33	68.28

LM *i*: Individual Linear Models

LM 1: Linear Model inc. lum

LM 2: Linear Model ex. lum

LM 0: Linear Model 1 with original road centrelines

4.5. Final Model Analysis

For a more comprehensive analysis of the overall suitability of the road width linear probability models, and a comparison between them, a quantitative assessment must be undertaken, this allows for the inclusion of all roads in the study.

For direct comparison between the two selected global linear probability models, centering and scaling of the predictor variables allowed for an easier interpretation of results, without affecting any statistical inferences. This was considered necessary as both P values and standard errors produced by global models offered little in terms of interpretability due to the very large number of points involved in this study. Centering and scaling was obtained through the production of beta coefficients with results given on Table 4.1. While the removal of *luminescence* has had little effect on the other predictor coefficients, due to the very small influence of this coefficient, reflected by the normalised value (0.01), and the qualitative analysis of the issues due to shadows, is was considered an unnecessary addition. The other coefficients all give insight into their influence of the road outcome, for example for every 1 increase in the standard deviation in *dist*, the likelihood a point is to be a road point decreases by a standard deviation of 0.33. This therefore suggests that the inclusion of the *dist* coefficient is important, despite not considered in other supervised road detection techniques.

Table 4.2 gives a normalised comparison between each linear model, and its associated estimated road width. This gives insight into the effectiveness of various linear probability models for each road, and road type. While average values all give relative accuracy in the region of 70%, it appears likely that without adjusting the road centrelines, model probabilities are reduced given LM 0 gives the lowest average accuracy in relation to the other three models using improved centrelines for outcome variable creation. Unexpectedly, the roads with the highest accuracy are Local and Minor Roads, rather than B roads. For certain roads, the accuracy of the derived centrelines appear to vastly reduce model accuracy, (For example Road 14; Table 4.2).

4.6. Road Assessment

Given Linear Model 2 with corrected road centrelines appears to produce the most accurate estimates for road widths, this was used in the final road assessment. Table 4.3 gives the full results of the road geometric extraction, along with an estimate of overall road quality given by the Road Quality Index (RQI). Qualitative assessment of the RQI may be achieved through observation of the highest and lowest values (Figure 4.6). It appears to produce reliable results, as the road with the highest RQI is straight, wider than the road with the lowest RQI, and is likely flat given it is neighboured by two agricultural fields.



Fig. 4.6: Visual comparison between road with the highest RQI (A), and lowest RQI (B)

Table 4.3: Overall Features Extracted from Roads in the Study Area, in descending order by RQI value

Road ID	Road Function	Max Angle	Total Z	Intensity	Width (LM 2)	Reliability (P_n/L)	RQI
34	Minor Road	0.00	2.82	40	4.87	14.19	0.89
15	B Road	0.01	7.49	62	4.99	0.93	0.60
20	Local Road	0.00	1.26	319	4.95	3.90	0.18
16	B Road	0.00	7.55	167	3.88	1.04	0.00
1	B Road	0.00	3.02	281	3.91	1.26	-0.08
21	B Road	0.01	2.41	155	2.89	2.02	-0.14
9	Minor Road	17.15	7.31	64	4.07	0.69	-0.19
18	Minor Road	9.51	3.84	101	2.95	0.46	-0.34
36	Minor Road	14.58	6.95	125	3.79	0.84	-0.36
13	B Road	0.00	3.62	313	3.14	0.74	-0.52
7	B Road	0.06	7.10	299	3.39	3.83	-0.55
4	Minor Road	12.81	7.29	382	4.73	4.33	-0.79
10	Minor Road	17.95	12.08	277	4.85	4.97	-0.89
30	Minor Road	24.53	4.93	252	3.74	3.63	-0.96
8	Minor Road	7.08	10.63	346	3.73	0.38	-0.97
31	Minor Road	10.33	11.04	251	3.33	0.53	-0.99
33	Minor Road	18.16	11.33	309	3.52	4.08	-1.35
12	Minor Road	18.51	15.85	370	4.17	2.03	-1.55
6	Minor Road	30.38	14.03	384	4.22	2.55	-1.87
14	Local Road	16.66	19.91	233	2.52	0.37	-2.11

5. Discussion

THE proposed methodology provides a road classification method which considers the need for an optimised and efficient extraction of road widths to combine with other road features and geometry for use in an automated national road assessment. This method builds upon past classification methodologies with the inclusion of Ordnance Survey road centreline geometries allowing for a supervised classification, without the need for the manual and time consuming creation of a training dataset. The primary goal is primarily to provide a fully scalable classification, for a national rural assessment for all roads in England, given access to Ordnance Survey centrelines, and LiDAR point cloud data.

The results of this paper can be considered to present the overall goal of automated road feature extraction, split into two main sections, the first being automated road width extraction, and second, the automated extraction of other road features.

5.1. Discussion of the Method

As results have revealed, it is relatively hard to quantify the results of this particular linear probability analysis, and often the accuracy of results has been assessed qualitatively. The ultimate goal with this method would be to produce a model which may be assessed quantitatively, allowing for a more conclusive and full automation.

5.1.1. Alternatives to Linear Probability

Alternatives to Linear Probability models do exist when considering binary outcome variables, one being probabilistic regression, which takes the cumulative standard normal distribution function (Φ) to model the regression. Interpretability of results may be aided through this method as it includes consideration of the quantiles associated with a unit change in outcome variables. Additionally logistic (and probabilistic) regression, unlike simple linear regression do not take the assumption that there is a linear distribution in the outcome, weighting values more towards 1 or 0, conforming more with the distribution of a binary outcome variable (See Figure 5.1; Hanck et al. 2019). However, preliminary analysis of the methodology performed in this study did consider a logistic regression, but found that interpretability of the quantiles and results was difficult, and qualitative observation of the results did not appear to provide much benefit over linear regression.

5.1.2. Computational Efficiency

Direct comparison between the computational efficiency of this method and past methods is not possible due to the unique data used in this study. However, Zhang et al. (2016) outline some specifications of the dataset used in their supervised road centreline extraction using LiDAR and aerial imagery. With aerial imagery at a resolution of 15cm, and a total 5200 by 5000 pixels, the study area therefore covers 780m by 750m. Similar to the 1km² for this study. The total time taken for object extraction for this area in their method was 37.87 minutes, compared with the 15.45 minutes proposed in this paper. It is expected that the method proposed by Zhang et al. (2016) should take far longer to compute due to being the inclusion of complex methodologies

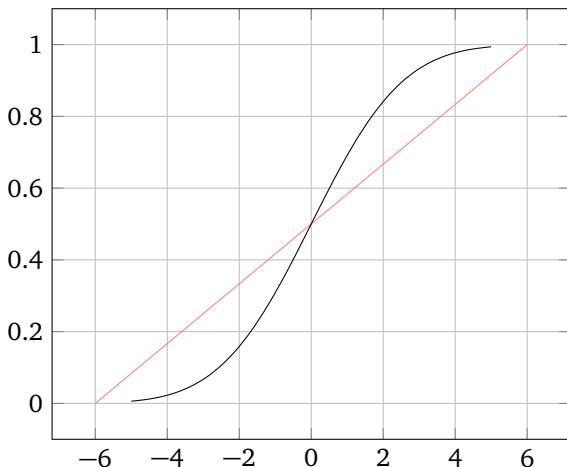


Fig. 5.1: Comparison between a Linear Probability Model Distribution (Red) and Probit/Logit Cumulative Standard Normal Distribution (Black) (Approximation credit [Bowling et al. 2009](#)))

such as image segmentation through random forest classification. Additionally the methodology proposed by [Zhang et al. \(2016\)](#) and other supervised road classification techniques rely on the existence of a training dataset, either derived through manual image segmentation, or the preexisting full road location data itself. While many past studies have focused on unsupervised methods (e.g. [Clode et al. 2004](#), [Vosselman 2009](#), [Jaakkola et al. 2008](#), [Darmawati 2008](#)), with the exclusion of any training data. The method proposed here suggests an intermediate between the two, given road centreline locations are freely obtainable, I propose that practical applications of road classification should focus more on the inclusion of such data, allowing for the increased accuracy and lower complexity that supervised road classification techniques provide, without the reliance on a full training dataset, with a similar (but different) application coined *Partially Supervised Classification* by [Guan et al. \(2013\)](#).

5.1.3. Comparison with Similar Studies

Despite several road classification methodologies proposing the inclusion of aerial imagery to assist with accuracy (e.g. [Charaniya et al. 2004](#), [Hui et al. 2008](#), [Guan et al. 2013](#)), this study reveals that for roads overlooked by tall features such as hedgerows, the shadow created reduces the overall classification accuracy. Additionally, the inclusion of aerial data provided little benefit in areas without shadows, likely due to the more distinct separation in intensity values from road surface and surrounding vegetation, unlike that found in a more urban setting.

Due to the irregularity of LiDAR and the large number of points, many past road classification techniques have relied on regulating the data into a grid ([Hatger 2005](#)). For example, [Clode et al. \(2004\)](#) used LiDAR with a resolution of 0.8m, and regularised this into a grid to produce a DTM and subsequently extract road centrelines. Due to this aggregation, they were able to filter points through a density threshold, and produce road centrelines. However, using this method to find road widths proved more difficult, and as [Hatger \(2005\)](#) note, the function that derived road widths in this paper resulted in some ambiguity.

The focus of many road classification techniques are primarily directed towards either centreline extraction ([Clode et al. 2004](#), [Zhang et al. 2018](#), [Matkan et al. 2014](#)), or the use of ground based LiDAR for use in automated vehicles ([Jaakkola et al. 2008](#), [Yoon & Crane 2009](#)), and almost all studies appear to focus on urban road classification ([Li et al. 2016](#), [Vosselman 2009](#), [Zhao & You 2012](#)), while even studies considering "rural" areas, do not represent roads that would be found in the context of rural England ([Azizi et al. 2014](#), [Mena & Malpica 2005](#)), and exclude key features such as hedgerows, overhanging vegetation, and appear fully

distinct from surrounding areas. Additionally these studies do not focus primarily on road width extraction, and as such are limited by the requirement for the inclusion of all points of data, to obtain a full road extraction. The methodology presented has a clear focus on the road feature extraction, without the requirement for road centreline extraction which is already accounted for nationally. Due to this, the novel technique for extraction allows for both sampling of the point cloud, leading to far lower computational requirements, while enabling simplistic filtering for noise and width extraction.

The study of the speed accident relationship on rural British roads by [Taylor et al. \(2002\)](#) outlined some techniques for the extraction of rural British road features, and as such was able to begin an assessment for the classification of rural road hierarchies. However, the techniques employed did not allow for a scalable approach, using drive through video recordings, and often lacked in accuracy, taking the road height variation from OS 10m contour lines. The method proposed here aims to alleviate these problems by ensuring a higher level of accuracy in height variation, through the use of LiDAR data with a +/-25cm RMSE. As well as allowing for a computational technique that does not rely on the manual collection of road level data, and instead uses aerial LiDAR which is more practically feasible to obtain for a comprehensive study, given the multiple use cases LiDAR has.

5.2. Applications of this Methodology

5.2.1. Stopping Sight Distance

Stopping Sight Distances are an important consideration for rural British roads, from qualitative observation of aerial imagery, and personal knowledge, hedgerows that bank the verges either side of many rural British roads often fully obscure the sight line around sharp bends, meaning it is often impossible to see oncoming traffic or obstacles, which, given the nature of these roads can often be large farm vehicles which spill into multiple lanes, or hazards such as farm animals, or unsafe road conditions. It is worth mentioning that the majority of hedgerows have automatic protection under the Hedgerow Regulations 1997 ([UK Government 1997](#)) for numerous historic and environmental reasons (e.g. protected species; [UK Government 1981](#)), as such, their removal for road safety is rarely granted.

Stopping Sight Distance is defined as the ability to see an object in the roadway with enough distance to stop, [5.1](#) outlines the calculated stopping sight distances at certain speeds, giving a rough indication of the distance required between a car and bend in a road. For example, [5.1](#) indicates that at 100kph (60mph), stopping sight distance is recommended to be 185m. Broadly, for a road to be considered appropriate for a 60mph limit, it could be said that it should not have a bend which impairs the line of sight more than every 185m, or a requirement of at most 5.4 bends per km. Roughly quantifying this, given the number of changes in road direction per road segment, extracted from the OS Road centreline geometries, none of the observed roads achieve this, while some roads have an excess of 100 bends per km.

Assumptions for certain road regulations are made that drivers will slow to appropriate speeds to adapt to road conditions, either in poor weather, or to approach a sharp bend, however [Layton & Dixon \(2012\)](#) note that often this is not that case, and drivers often do not slow appreciably to account for these conditions. Therefore, the consideration that speed limits should more accurately reflect the conditions of the road. Additionally, stopping sight distances observed by [Layton & Dixon \(2012\)](#) are significantly longer for larger vehicles such as trucks, given the large farm vehicles often present on country roads, speed policy should take this into account.

Road features extracted may be used to inform the current likely stopping sight distances, combining key features such as the width of roads, which influences the sight line, the max bend angle within a road

Table 5.1: Recommended minimum Stopping Sight Distances at certain speeds (*Layton & Dixon 2012*)

Speed (km/h)	Stopping Sight Distance		Typical Emergency Stopping Distance (m)	
	Calculated (2.5^s , $a=3.4m/s^2$)	Design (2.5^s , a)	Wet Pavement (1^s , f_{wet})	Dry Pavement (1^s , f_{dry})
30	31.2	35	17.1	14.2
40	46.2	50	27.7	21.6
50	63.5	65	42.0	30.3
60	83.0	85	59.6	40.3
70	104.9	105	81.7	51.6
80	129.0	130	106.1	64.2
90	155.5	160	131.2	78.1
100	184.2	185	163.4	93.4
110	215.3	220	200.6	110.0
120	248.6	250	235.7	127.9

segment, and the elevation change. For information regarding the calculated number of bends per kilometer in this study, see Table B.1.

5.2.2. Rural Accessibility

Accessibility has several definitions, either in terms of economic and social opportunity, or as a proximity and facility for spatial interaction [Gutiérrez \(2009\)](#). Transport disadvantage is a key limitation of physical accessibility, that may be either due to limitations such as lack of public transport, a poor road network, or a persons physical inability to reach a destination due to disability ([Smith et al. 2012](#)). Often transport disadvantage may be alleviated through access to public transport, as this removes the requirement for private transport ownership, limited by both income and ability to drive. However, public transport in rural areas is often limited or absent, meaning rural transport predominantly relies on private road vehicles, limiting access for those two are unable to drive, such as children, the elderly, and people with disabilities ([Manthorpe et al. 2008](#)). Additionally, this reliance of private transport increases the minimum cost of living in rural communities, given car ownership is often considered mandatory and often isn't taken into account when assessing the minimum cost of living in rural areas ([Smith et al. 2012](#)). For those who are unable to access private transport, this limit accessibility is considered limited through capability, rather than pure accessibility through journey times and other factors ([Currie 2010](#)). Rural areas in particular often have larger elderly populations, meaning capability is often a key issue in areas with poor public transport, and can lead to social exclusion for those without cars ([Solomon & Titheridge 2009](#)). Often there are special services in place for easily definable groups that attempt to alleviate the issue with transport disadvantage and social exclusion, such as free bus travel for the elderly, however, these services often do not account for those who are transport disadvantaged but are not easily defined, particularly for those who have no access to public transport ([Mulley & Nelson 2009](#))

Accessibility to destinations is often defined through journey times for populations to particular key services, in particular, the UK Government uses official accessibility indicators to set minimum thresholds for journey time access to education, health services, employment and retail hubs ([Department for Transport 2016](#)), also taking into account the availability of public transport services. Accessibility in rural areas is found to be far poorer than urban areas based off minimum travel times to various services, and while travel by car generally reduces travel times, the rate is still far below urban areas. To fully understand the implication of such analysis, the underlying data should also be considered. As mentioned, the accessibility index produced by the UK Government uses underlying journey times obtained through separate analysis based on theoretical journey times using public transport times, and average traffic speeds for areas ([Department for Transport 2018a](#)). This data is simplified, giving the start point of journeys as a single point within Output

Area census units, and aggregated road speeds. The output of this data is given at the LSOA level which is then used for accessibility analysis. Journey times are obtained through mass collection of GPS data by INRIX [INRIX \(2019\)](#) which is then used in TRACC software [TRACC \(2019\)](#).

Rural healthcare accessibility is becoming more of an issue given fewer healthcare professionals now live in rural communities, ([Farmer et al. 2003](#)), and the urban centralisation of hospital services ([Mungall 2005](#)), means that understanding the level of access that each rural community has to these services is more important than ever. Additionally, improving the understanding of rural road networks will enable improved emergency response times.

There is a strong urban bias for the development of new transport technologies ([Malecki 2003](#)), explained through key issues particular to rural transport systems;

- **Service area:** Rural transport agencies often serve large areas with long trips. As a result, assisting passengers needs is not easy and attending immediately to a problem that arises on the road is difficult (e.g. rescheduling trips when an incident occurs.)
- **Service Coordination:** There are different basic public services e.g. healthcare and education with overlapping areas of services. It is challenging to coordinate services and resources among the agencies and other providers.
- **Infrastructure:** Rural areas suffer a lack of communication infrastructure e.g. wireless communications services, real-time communication from and to rural passengers.
- **Fleet size:** Although tech can solve several transportation problems in remote rural areas, it might be difficult to fund and develop at a small scale.

([Riva et al. 2011](#))

While it may appear that many of these issues are inherent to rural areas, and unsolvable, the optimisation of transport technologies for rural areas may be made more achievable through access to the comprehensive road data provided through the methods proposed in this paper. [Palmer et al. \(2004\)](#) state that flexible integrated transport services are a likely public transport implementation that would benefit rural areas without the limitations outlined above, such a technology would rely extensively on a full understanding of the road network on which it would be dispatched.

[Mulley & Nelson \(2009\)](#) state that the demand for a full implementation of public transport systems in many rural areas often does not justify demand, and local authorities rely on optimisation of funding, which has led to the discontinuation of many rural public transport networks. This calls for developments for the alleviation of social exclusion, that do not employ conventional solutions. The [Department for Transport \(2016\)](#) call for "Unconventional modes" of public transport in such areas, building mainly on a bottom up approach to meet direct demand, additionally vehicles supplied through such an implementation would account for suitability to both road conditions and consumer demand, allowing for vehicles smaller than a typical bus for example ([Mulley & Nelson 2009](#)).

There is a significant call for the inclusion of a more comprehensive understanding of the road network through advanced computational techniques to improve the efficiency and quality of existing transport systems ([Deeter 2009](#)), including a more flexible transport management system ([Robinson 2008](#)). Technologies are already used frequently to make mainstream public services more effective and efficient, such as healthcare and education ([Boulton 2010](#)).

The divide between rural and urban health outcomes has been shown to relate to social mobility and migration of healthier and more socially mobile groups into rural areas, leaving behind less mobile groups in

urban settings (Riva et al. 2011). Net movement out of rural areas is particularly influenced primarily by young adults moving to urbanised areas (Champion 2004). While Riva et al. (2011) suggest that social mobility is purely the reason for improved health outcomes in rural England, particularly given there is evidence to suggest that urban centralisation of hospital services should have a negative impact on rural health outcomes (Haynes & Gale 2000, Farmer et al. 2003). The question therefore presents itself; what is driving out those with less social mobility, and young adults? Given health outcomes in rural areas are broadly better than those in urban areas, and have been for some time (Watt et al. 1994), why do certain groups select urban areas over rural?

The methodology I have presented would allow for an accurate journey time prediction that does not rely on the complex aggregation of expensive GPS data which is then aggregated to census units. It is likely that for significantly rural areas, particularly those with poor GPS connections, this road speed information is likely particularly inaccurate, often in consumer grade GPS systems, optimal routes chosen appear to, more often than not, choose the most direct route when presented with a rural road network, rather than select a route based on an accurate assessment of the true speed achievable on a route. The proposed method will allow for estimations based on true features of roads, including width, height change, bends and surface quality to produce an assessment to determine the likely journey times for each individual road within any rural area covered. Particularly, Hodge & Monk (2004) state that generalisation of the countryside is dangerous, as due to the sparse population of such areas, aggregation typically groups areas which feature a range of different problems, it makes sense that for a better understanding of rural accessibility in relation to the road network, the focus should be at the road level, and not an aggregation into census units.

5.2.3. Other Applications

Supply chains rely on a well maintained road infrastructure, and as such, many rural areas are considered to be "Lagging Rural Regions", due to their geographical remoteness, poor infrastructures, low population density and limited employment opportunities, often supported economically by an agricultural backbone (Ilbery et al. 2004). Improving the economy of such areas therefore relies primarily on the effectiveness of the supply chains, often limited due to the poor infrastructures (Marsden et al. 2002), and recent demand for large scale supply chains is limited in these areas due to the overall quality of the road network. To further understand the limitations of rural supply chains inherently relies on a full understanding of the road network, whether to acknowledge where limitations exist, or to develop opportunities for optimisation of the supply chains. Bosona & Gebresenbet (2011) call for location analysis of supply chains through quantifiable data, to better optimise supply routes.

5.3. Limitations and Improvements

5.3.1. Classification optimisation

At present the removal of noise at the final stage of the road classification comes from both identifying isolated points A.2.17, and the removal of calculated widths that are above 8m and below 2m C. While logically it makes sense to include limitations for widths, given a road below 2m would not support even single way traffic, and a 8m road is unexpected for any rural single carriageway, these limitations are still arbitrary, and for all unclassified roads in England, there is no minimum width required (Highways England 2016).

Alternative methods to reduce the noise produced by this method may include the identifications of straight line road edges, a distinguishing feature of man made structures Guan et al. (2013). This could enable point exclusion if outside of a particular threshold in relation to other points. LiDAR classification techniques often make use of segmentation algorithms to identify objects from geometric features such as planes, and straight

edges (Wang & Shan 2009). These include Hough transforms (Vosselman et al. 2004, Clode et al. 2004), RANSAC (Smadja et al. 2010, Sampath & Shan 2008), and least square fitting (Matkan et al. 2014).

It should also be noted that the quantile selection at present is based on a qualitative observation of the distribution of linear probability values for the current 1km² area, and as such it would be essential to find a method to quantitatively assess the required quantile.

5.3.2. *Limitation of this Method*

Driving behaviour is affected by particular features that are not covered in this methodology, namely the delineation of road centrelines and edges (Steyvers & De Waard 2000, Charlton et al. 2018). The detection of these features is influenced by both the quality of the road, if a road edge is easily detectable, or if a road has painted markings to indicate a centreline, both of which are not observable through this methodology, and would likely rely on mobile LiDAR data collection.

An assumption is made that roads are a constant width, however, due to using road id, representing the sections between junctions, means that average road length was 236.8634483, and it is unlikely that width changes significantly over this generally. The current inaccuracy of this method however relies on the aggregation of road sampled widths to provide an overall mean for a road, and as such is unable to provide accurate information regarding a road at any given point.

Additionally Hatger (2005) note that a road network is an interconnected grid, and as such, there should be more emphasis on bridging gaps between road segments that are unable to be identified. While this would introduce some assumptions, it would be worth considering the possibility of producing a result that connects all samples to form a true representation of road geometries.

6. Conclusion

Method that provides a ground between simplistic filtering methods, and more complex methods such as deep learning neural networks, using the resources produced by government ran organisations.

Bibliography

- Aarts, L. & van Schagen, I. (2006), 'Driving speed and the risk of road crashes: A review', *Accident Analysis & Prevention* **38**(2), 215–224. ZSCC: 0000994.
- Aquino, J. (2019), *nvimcom: Intermediate the Communication Between R and Either Neovim or Vim*. R package version 0.9-83.
URL: <https://github.com/jalvesaq/nvimcom>
- Arnold, J. B. (2019), *ggthemes: Extra Themes, Scales and Geoms for 'ggplot2'*. R package version 4.2.0.
URL: <https://CRAN.R-project.org/package=ggthemes>
- Axelsson, P (1999), 'Processing of laser scanner data—algorithms and applications', *ISPRS Journal of Photogrammetry and Remote Sensing* **54**(2-3), 138–147. ZSCC: 0000940.
- Azizi, Z., Najafi, A. & Sadeghian, S. (2014), 'Forest Road Detection Using LiDAR Data', *Journal of Forestry Research* **25**(4), 975–980. ZSCC: 0000030.
- Bache, S. M. & Wickham, H. (2014), *magrittr: A Forward-Pipe Operator for R*. R package version 1.5.
URL: <https://CRAN.R-project.org/package=magrittr>
- Baruya, A. (1998), 'MASTER: Speed-accident relationship on European roads'. ZSCC: 0000014.
- BBC (2012), 'Plan for 40mph country road limit', *BBC News* . ZSCC: 0000000[s1].
- Bengtsson, H. (2019), *future: Unified Parallel and Distributed Processing in R for Everyone*. R package version 1.14.0.
URL: <https://CRAN.R-project.org/package=future>
- Bivand, R., Keitt, T. & Rowlingson, B. (2019), *rgdal: Bindings for the 'Geospatial' Data Abstraction Library*. R package version 1.4-4.
URL: <https://CRAN.R-project.org/package=rgdal>
- Bosona, T. & Gebresenbet, G. (2011), 'Cluster building and logistics network integration of local food supply chain', *Biosystems Engineering* **108**(4), 293–302. ZSCC: 0000139.
- Boulton, G. (2010), 'Digital Scotland', *Report by Royal Society of Edinburgh* . ZSCC: 0000004.
- Bowling, S. R., Khasawneh, M. T., Kaewkuekool, S. & Cho, B. R. (2009), 'A logistic approximation to the cumulative normal distribution', *Journal of Industrial Engineering and Management* **2**(1), 114–127. ZSCC: 0000087.
- Bridson, R., Marino, S. & Fedkiw, R. (2005), Simulation of clothing with folds and wrinkles, in 'ACM SIGGRAPH 2005 Courses on - SIGGRAPH '05', ACM Press, Los Angeles, California, p. 3. ZSCC: 0000550.
- Champion, A. (2004), 'Patterns of Net Migration in England in the Context of the Urban_Rural Definition, Census 2001', *Rural Evidence Research Centre* . ZSCC: 0000002.
- Charaniya, A., Manduchi, R. & Lodha, S. (2004), Supervised Parametric Classification of Aerial LiDAR Data, in '2004 Conference on Computer Vision and Pattern Recognition Workshop', IEEE, Washington, DC, USA, pp. 30–30. ZSCC: 0000166.
- Charlton, S. G., Starkey, N. J. & Malhotra, N. (2018), 'Using road markings as a continuous cue for speed choice', *Accident Analysis & Prevention* **117**, 288–297. ZSCC: 0000005.
- Clode, S., Kootsookos, P & Rottensteiner, F. (2004), 'The Automatic Extractin of Roads from LiDAR Data', p. 7. ZSCC: NoCitationData[s1].
- Corben, B., Oxley, J., Koppel, S. & Johnston, I. (2005), 'Cost-effective measures to improve crash and injury risk at rural intersections.', p. 10. ZSCC: 0000004.
- Currie, G. (2010), 'Quantifying spatial gaps in public transport supply based on social needs', *Journal of Transport Geography* **18**(1), 31–41.
- Darmawati, A. (2008), Utilization of multiple echo information for classification of airborne laser scanning data, ITC. ZSCC: 0000013.
- Deeter, D. (2009), 'Real-time traveler information systems. NCHRP report 399', *Transport Research Board, USA* . ZSCC: 0000004.
- Department for Transport (2006), 'Speed Assessment Framework', <http://www2.dft.gov.uk/>. ZSCC: NoCitationData[s0].
- Department for Transport (2011), 'Strategic framework for road safety'. ZSCC: 0000006.
- Department for Transport (2012), 'Guidance on road classification and the primary route network', p. 26. ZSCC: 0000005.
- Department for Transport (2013a), 'Setting local speed limits', p. 42. ZSCC: 0000004[s1].
- Department for Transport (2013b), 'The Speed Limit Appraisal Tool: User Guidance', p. 93. ZSCC: 0000000[s1].
- Department for Transport (2016), 'Overall measure of accessibility of services'. ZSCC: NoCitationData[s0].
- Department for Transport (2018a), 'Journey Time Statistics'. ZSCC: NoCitationData[s0].
- Department for Transport (2018b), 'Road Conditions in England 2017', p. 8. ZSCC: NoCitationData[s0].
- Department for Transport (2018c), 'Road Safety Management Capacity Review'. ZSCC: NoCitationData[s1].
- Department for Transport (2019), 'Road traffic statistics - Summary statistics', <https://roadtraffic.dft.gov.uk/summary>. ZSCC: 0000000[s1].

BIBLIOGRAPHY

- Dowle, M. & Srinivasan, A. (2019), *data.table: Extension of 'data.frame'*. R package version 1.12.2.
URL: <https://CRAN.R-project.org/package=data.table>
- Dubes, R. & Ohanian, P. (1992), 'Performance evaluation for four classes of textural features', *Pattern Recognition* **25**, 819–833. ZSCC: 0000550.
- Elberink, S. O. & Maas, H.-G. (2000), 'The Use of Anisotropic Height Texture Measures for the Segmentation of Airborne Laser Scanner Data', p. 8. ZSCC: 0000116.
- Environment Agency (2019), 'LiDAR', <https://data.gov.uk/dataset/977a4ca4-1759-4f26-baa7-b566bd7ca7bf/lidar-point-cloud>. ZSCC: NoCitationData[s1].
- ESRI (2019), 'Lidar point classification—Help | ArcGIS Desktop', <http://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/lidar-point-classification.htm>.
- Farmer, J., Lauder, W., Richards, H. & Sharkey, S. (2003), 'Dr. John has gone: Assessing health professionals' contribution to remote rural community sustainability in the UK', *Social Science & Medicine* **57**(4), 673–686. ZSCC: 0000092.
- Ferchichi, S. & Shengrui Wang (2005), Optimization of cluster coverage for road centre-line extraction in high resolution satellite images, in 'IEEE International Conference on Image Processing 2005', Vol. 2, pp. II–201. ZSCC: 0000010.
- Ferraz, A., Mallet, C. & Chehata, N. (2016), 'Large-scale road detection in forested mountainous areas using airborne topographic lidar data', *ISPRS Journal of Photogrammetry and Remote Sensing* **112**, 23–36. ZSCC: 0000038.
- Finch, D., Kompfner, P., Lockwood, C. & Maycock, G. (1994), 'Speed, Speed Limits and Accidents', <https://trl.co.uk/sites/default/files/PR058.pdf>. ZSCC: 0000234.
- Fleming, P., Frost, M. & Lambert, J. (2009), Lightweight deflectometers for quality assurance in road construction, in 'IN: Tutumluer, E. and Al-Qadi, IL (Eds). Bearing Capacity of Roads, Railways and Airfields: Proceedings of the 8th International Conference (BCR2A'09)', Taylor & Francis Group, pp. 809–818. ZSCC: 0000017.
- Francois, R. (2017), *bibtex: Bibtex Parser*. R package version 0.4.2.
URL: <https://CRAN.R-project.org/package=bibtex>
- Garnier, S. (2018a), *viridis: Default Color Maps from 'matplotlib'*. R package version 0.5.1.
URL: <https://CRAN.R-project.org/package=viridis>
- Garnier, S. (2018b), *viridisLite: Default Color Maps from 'matplotlib' (Lite Version)*. R package version 0.3.0.
URL: <https://CRAN.R-project.org/package=viridisLite>
- Gillespie, C. (2019), *benchmarkme: Crowd Sourced System Benchmarks*. R package version 1.0.2.
URL: <https://CRAN.R-project.org/package=benchmarkme>
- Gray, D., Farrington, J., Shaw, J., Martin, S. & Roberts, D. (2001), 'Car dependence in rural Scotland: Transport policy, devolution and the impact of the fuel duty escalator', *Journal of Rural Studies* **17**(1), 113–125. 00075.
- Guan, H., Ji, Z., Zhong, L., Li, J. & Ren, Q. (2013), 'Partially supervised hierarchical classification for urban features from lidar data with aerial imagery', *International Journal of Remote Sensing* **34**(1), 190–210. ZSCC: 0000020.
- Gutiérrez, J. (2009), 'Transport and accessibility'. ZSCC: 0000038.
- Hanck, C., Arnold, M., Gerber, A. & Schmelzer, M. (2019), 'Introduction to Econometrics with R', p. 392. ZSCC: NoCitationData[s0].
- Harrell Jr, F. E., with contributions from Charles Dupont & many others. (2019), *Hmisc: Harrell Miscellaneous*. R package version 4.2-0.
URL: <https://CRAN.R-project.org/package=Hmisc>
- Hatger, C. (2002), 'On the use of Airborne Laser Scanning Data to Verify and Enrich Road Network Features', p. 6. ZSCC: 0000013.
- Hatger, C. (2005), 'Road extraction by use of airborne laser scanner data', p. 19. ZSCC: 0000001.
- Haynes, R. & Gale, S. (2000), 'Deprivation and poor health in rural areas: Inequalities hidden by averages', *Health & Place* **6**(4), 275–285. ZSCC: 0000138.
- Highways England (2016), 'Letter in response to road width restrictions. FOI: 734,857'.
- Highways England (2019), 'Network management'. ZSCC: 0000000.
- Hijmans, R. J. (2019), *raster: Geographic Data Analysis and Modeling*. R package version 3.0-2.
URL: <https://CRAN.R-project.org/package=raster>
- Hodge, I. & Monk, S. (2004), 'The economic diversity of rural England: Stylised fallacies and uncertain evidence', *Journal of Rural Studies* **20**(3), 263–272.
- Hu, X., Tao, C. V. & Hu, Y. (2004), 'Automatic Road Extraction from Dense Urban Area by Integrated Processing of Height Resolution Imagery and LiDAR Data', p. 5. ZSCC: 0000149.
- Hui, L., Di, L., Xianfeng, H. & Deren, L. (2008), 'Laser Intensity Used in Classification of Lidar Point Cloud Data', in 'IGARSS 2008 - 2008 IEEE International Geoscience and Remote Sensing Symposium', IEEE, Boston, MA, USA, pp. II–1140–II–1143. ZSCC: 0000016.
- Ihaka, R. (2011), 'Rnoweb: Literate Programming with and for R', p. 5. ZSCC: 0000000.
- Ilbery, B., Maye, D., Kneafsey, M., Jenkins, T. & Walkley, C. (2004), 'Forecasting food supply chain developments in lagging rural regions: Evidence from the UK', *Journal of Rural Studies* **20**(3), 331–344. ZSCC: 0000148.
- INRIX (2019), 'INRIX', <http://inrix.com/>. ZSCC: NoCitationData[s0].
- Jaakkola, A., Hyypä, J., Hyppä, H. & Kukko, A. (2008), 'Retrieval Algorithms for Road Surface Modelling Using Laser-Based Mobile Mapping', *Sensors* **8**(9), 5238–5249. ZSCC: 0000162.
- Kassambara, A. (2019), *ggpubr: 'ggplot2' Based Publication Ready Plots*. R package version 0.2.2.
URL: <https://CRAN.R-project.org/package=ggpubr>
- Knuth, D. E. (1984), 'Literate programming', *The Computer Journal* **27**(2), 97–111. ZSCC: 0002155.
- Kraus, K. & Pfeifer, N. (1998), 'Determination of terrain models in wooded areas with airborne laser scanner data', *ISPRS Journal of Photogrammetry and Remote Sensing* **53**(4), 193–203. ZSCC: 0001405.
- Kumar, P., McElhinney, C. P., Lewis, P. & McCarthy, T. (2013), 'An automated algorithm for extracting road edges from terrestrial

BIBLIOGRAPHY

- mobile LiDAR data', *ISPRS Journal of Photogrammetry and Remote Sensing* **85**, 44–55. ZSCC: 0000088.
- Layton, R. & Dixon, K. (2012), 'Stopping sight distance', *Kiewit Center for Infrastructure and Transportation, Oregon Department of Transportation*. ZSCC: 0000037.
- Leutner, B., Horning, N. & Schwalb-Willmann, J. (2019), *RStoolbox: Tools for Remote Sensing Data Analysis*. R package version 0.2.6.
URL: <https://CRAN.R-project.org/package=RStoolbox>
- Li, Y., Hu, X., Guan, H. & Liu, P. (2016), 'An Efficient Method for Automatic Road Extraction Based on Multiple Features from LiDAR Data', *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **XLI-B3**, 289–293.
- Maas, H.-G. (1999), 'The Potential of Height Texture Measures for the Segmentation of Airborne Laserscanner Data', p. 8. ZSCC: 0000134.
- Mahmoudian, M. (2018), *varhandle: Functions for Robust Variable Handling*. R package version 2.0.3.
URL: <https://CRAN.R-project.org/package=varhandle>
- Malecki, E. (2003), 'Digital Development in Rural Areas: Potentials and Pitfalls', *Journal of Rural Studies* **19**, 201–214.
- Manthorpe, J., Iliffe, S., Clough, R., Cornes, M., Bright, L., Moriarty, J. & Older People Researching Social Issues (2008), 'Elderly people's perspectives on health and well-being in rural communities in England: Findings from the evaluation of the National Service Framework for Older People', *Health & social care in the community* **16**(5), 460–468. ZSCC: NoCitationData[s0].
- Marsden, T., Banks, J. & Bristow, G. (2002), 'The social management of rural nature: Understanding agrarian-based rural development', *Environment and planning A* **34**(5), 809–825. ZSCC: 0000228.
- Matkan, A. A., Hajeb, M. & Sadeghian, S. (2014), 'Road Extraction from Lidar Data Using Support Vector Machine Classification', *Photogrammetric Engineering & Remote Sensing* **80**(5), 409–422. ZSCC: 0000022.
- Mena, J. & Malpica, J. (2005), 'An automatic method for road extraction in rural and semi-urban areas starting from high resolution satellite imagery', *Pattern Recognition Letters* **26**(9), 1201–1220. 00195.
- Moore, R., Carey, J., Mills, A., Martin, S., Irinder, S., Kerry, L., Leask, G., Simmons, A. & Ashaari, M. (2006), Recent landslide impacts on the UK Scottish road network: Investigation into the mechanisms, causes and management of landslide risk, in 'Proceedings of the International Conference on Slopes, Kuala Lumpur, Malaysia', Public Works Department, Kuala Lumpur, Malaysia, pp. 223–237. ZSCC: NoCitationData[s0].
- Mulley, C. & Nelson, J. D. (2009), 'Flexible transport services: A new market opportunity for public transport', *Research in Transportation Economics* **25**(1), 39–45. ZSCC: 0000133.
- Mungall, I. (2005), 'Trend towards centralisation of hospital services.', 00000.
- Nicholl, J., West, J., Goodacre, S. & Turner, J. (2007), 'The relationship between distance to hospital and patient mortality in emergencies: An observational study', *Emergency Medicine Journal* **24**(9), 665–668. 00162.
- Noctor, I. (2004), 'Change to kph limit to cost €30m', <https://www.irishtimes.com/life-and-style/motors/change-to-kph-limit-to-cost-30m-1.1133469>. ZSCC: NoCitationData[s0].
- Palmer, K., Dessouky, M. & Abdelmaguid, T. (2004), 'Impacts of management practices and advanced technologies on demand responsive transit systems', *Transportation Research Part A: Policy and Practice* **38**(7), 495–509.
- Pebesma, E. (2018), 'Simple Features for R: Standardized Support for Spatial Vector Data', *The R Journal* **10**(1), 439–446.
URL: <https://doi.org/10.32614/RJ-2018-009>
- Peterson, B. G. & Carl, P (2019), *PerformanceAnalytics: Econometric Tools for Performance and Risk Analysis*. R package version 1.5.3.
URL: <https://CRAN.R-project.org/package=PerformanceAnalytics>
- Peterson, R. A. & Brown, S. P. (2005), 'On the Use of Beta Coefficients in Meta-Analysis.', *Journal of Applied Psychology* **90**(1), 175–181.
- QGIS Development Team (2019), *QGIS Geographic Information System*, Open Source Geospatial Foundation.
URL: <http://qgis.org>
- Qiu, Y. & authors/contributors of the included software. See file AUTHORS for details. (2019), *showtext: Using Fonts More Easily in R Graphs*. R package version 0.7.
URL: <https://CRAN.R-project.org/package=showtext>
- R Core Team (2019), *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.
URL: <https://www.R-project.org/>
- Ram, K. & Wickham, H. (2018), *wesanderson: A Wes Anderson Palette Generator*. R package version 0.3.6.
URL: <https://CRAN.R-project.org/package=wesanderson>
- Richards, D. & Cuerden, R. (2009), 'The Relationship between Speed and Car Driver Injury Severity', p. 16. ZSCC: 0000045.
- Riva, M., Curtis, S. & Norman, P. (2011), 'Residential mobility within England and urban-rural inequalities in mortality', *Social Science & Medicine* **73**(12), 1698–1706. ZSCC: 0000050.
- Robinson, D. & Hayes, A. (2019), *broom: Convert Statistical Analysis Objects into Tidy Tibbles*. R package version 0.5.2.
URL: <https://CRAN.R-project.org/package=broom>
- Robinson, S. P. (2008), 'Determining London bus stop locations by means of an automatic vehicle location system', *Transportation Research Record* **2064**(1), 24–32. ZSCC: 0000007.
- Rottensteiner, F., Trinder, J., Clode, S. & Kubik, K. (2003), 'Building Detection Using LiDAR Data and Multi-spectral Images', p. 10. ZSCC: NoCitationData[s0].
- Roussel, J.-R. & Auty, D. (2019), *lidR: Airborne LiDAR Data Manipulation and Visualization for Forestry Applications*. R package version 2.1.2.
URL: <https://CRAN.R-project.org/package=lidR>
- Saeedi, S., Samadzadegan, F. & El-Sheimy, N. (2009), 'Object Extraction from LiDAR Data using an Artificial Swarm Bee Colony Clustering Algorithm', p. 6. ZSCC: 0000018.
- Sampath, A. & Shan, J. (2008), 'Building Roof Segmentation and Reconstruction from LiDAR Point Clouds using Clustering Techniques', p. 6. ZSCC: 0000022.
- Smadja, L., Ninot, J. & Gavrilovic, T. (2010), 'Road Extraction and Environment Interpretation from LiDAR Sensors', p. 6. ZSCC: 0000040.
- Smith, N., Hirsch, D. & Davis, A. (2012), 'Accessibility and capability: The minimum transport needs and costs of rural house-

BIBLIOGRAPHY

- holds', *Journal of Transport Geography* **21**, 93–101. ZSCC: 0000052.
- Solomon, J. & Titheridge, H. (2009), 'Setting accessibility standards for social inclusion: Some obstacles', p. 11.
- Solymos, P. & Zawadzki, Z. (2019), *pbapply: Adding Progress Bar to *apply Functions*. R package version 1.4-1.
URL: <https://CRAN.R-project.org/package=pbapply>
- Steyvers, F. J. J. M. & De Waard, D. (2000), 'Road-edge delineation in rural areas: Effects on driving behaviour', *Ergonomics* **43**(2), 223–238. ZSCC: 0000078.
- Stradling, S. G., Great Britain & Department for Transport (2008), *Understanding Inappropriate High Speed: A Quantitative Analysis*, Dept. for Transport, London. ZSCC: NoCitationData[s0]
OCLC: 277067852.
- Taylor, M. C., Baruya, A. & Kennedy, J. V. (2002), 'The relationship between speed and accidents on rural single-carriageway roads', p. 32. ZSCC: 0000125.
- Taylor, M. C., Lynam, D. A. & Baruya, A. (2000), 'The effects of drivers' speed on the frequency of road accidents', p. 56. ZSCC: 0000002.
- The University of Edinborough (2019), 'Aerial Digimap Educational User Licence', <https://digimap.edina.ac.uk/>. ZSCC: 0000000[s0].
- TRACC (2019), 'TRACC', <https://www.basemap.co.uk/tracc/>.
- UK Government (1981), 'Wildlife and Countryside Act 1981'.
- UK Government (1997), 'The Hedgerow Regulations 1997'.
- UK Government (2011), 'Rural Urban Classification', <https://www.gov.uk/government/collections/rural-urban-classification>. ZSCC: 0000347[s0].
- UK Government (2019a), 'Find open data - data.gov.uk', <https://data.gov.uk/>.
- UK Government (2019b), 'Speed limits', <https://www.gov.uk/speed-limits>. ZSCC: 0000773[s0].
- Velaga, N. R., Beecroft, M., Nelson, J. D., Corsar, D. & Edwards, P. (2012), 'Transport poverty meets the digital divide: Accessibility and connectivity in rural communities', *Journal of Transport Geography* **21**, 102–112. ZSCC: 0000141.
- Viner, H., Sinhal, R. & Parry, T. (2004), 'Review of UK skid resistance policy', *Preprint SURF*. ZSCC: 0000023.
- Vosselman, G. (2000), 'Slope Based Filtering of Laser Altimetry Data', p. 9. ZSCC: 0000833.
- Vosselman, G. (2009), 'Advanced Point Cloud Processing', p. 10. ZSCC: 0000074.
- Vosselman, G., Gorte, B. G., Sithole, G. & Rabbani, T. (2004), 'Recognising structure in laser scanner point clouds', *International archives of photogrammetry, remote sensing and spatial information sciences* **46**(8), 33–38. ZSCC: 0000541.
- Vosselman, G. & Zhou, L. (2009), 'Detection of curbstones in airborne laser scanning data', *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* **38**(Part 3/W8), 111–116. ZSCC: 0000030.
- Wan, Y., Shen, S., Song, Y. & Liu, S. (2007), A Road Extraction Approach Based on Fuzzy Logic for High-Resolution Multispectral Data, in 'Fourth International Conference on Fuzzy Systems and Knowledge Discovery (FSKD 2007)', Vol. 2, pp. 203–207. ZSCC: 0000014.
- Wang, J. & Shan, J. (2009), 'Segmentation of LiDAR Point Clouds for Building Extraction', p. 11. ZSCC: 0000076.
- Watt, I. S., Franks, A. J. & Sheldon, T. A. (1994), 'Health and health care of rural populations in the UK: Is it better or worse?', *Journal of Epidemiology & Community Health* **48**(1), 16–21.
- Wickham, H. (2014), *Advanced r*, Chapman and Hall/CRC. ZSCC: 0000183.
- Wickham, H. (2017), *tidyverse: Easily Install and Load the 'Tidyverse'*. R package version 1.2.1.
URL: <https://CRAN.R-project.org/package=tidyverse>
- Wickham, H. (2018), *scales: Scale Functions for Visualization*. R package version 1.0.0.
URL: <https://CRAN.R-project.org/package=scales>
- Wickham, H., Hester, J. & Chang, W. (2019), *devtools: Tools to Make Developing R Packages Easier*. R package version 2.1.0.
URL: <https://CRAN.R-project.org/package=devtools>
- Wilke, C. O. (2019), *cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2'*. R package version 1.0.0.
URL: <https://CRAN.R-project.org/package=cowplot>
- Williamson, P. (n.d.), *ENVS450: Helper functions for ENVS450*. R package version 0.1.0.
- Wu, K.-F., Donnell, E. T., Himes, S. C. & Sasidharan, L. (2013), 'Exploring the Association between Traffic Safety and Geometric Design Consistency Based on Vehicle Speed Metrics', *Journal of Transportation Engineering* **139**(7), 738–748. ZSCC: 0000027.
- Yadav, M., Lohani, B. & Singh, A. K. (2018), 'Road Surface Detection from Mobile LiDAR Data', *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* **IV-5**, 95–101. ZSCC: 0000000.
- Yoon, J. & Crane, C. D. (2009), Evaluation of terrain using LADAR data in urban environment for autonomous vehicles and its application in the DARPA urban challenge, in '2009 ICCAS-SICE', pp. 641–646. ZSCC: 0000011.
- Zhang, Shu-Ching Chen, Whitman, D., Mei-Ling Shyu, Jianhua Yan & Chengcui Zhang (2003), 'A progressive morphological filter for removing nonground measurements from airborne LiDAR data', *IEEE Transactions on Geoscience and Remote Sensing* **41**(4), 872–882. ZSCC: NoCitationData[s0].
- Zhang, W., Qi, J., Wan, P., Wang, H., Xie, D., Wang, X. & Yan, G. (2016), 'An Easy-to-Use Airborne LiDAR Data Filtering Method Based on Cloth Simulation', *Remote Sensing* **8**(6), 501. ZSCC: 0000112.
- Zhang, Z., Zhang, X., Sun, Y. & Zhang, P. (2018), 'Road Centerline Extraction from Very-High-Resolution Aerial Image and LiDAR Data Based on Road Connectivity', *Remote Sensing* **10**(8), 1284. ZSCC: 0000000.
- Zhao, J. & You, S. (2012), Road network extraction from airborne LiDAR data using scene context, in '2012 IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops', IEEE, Providence, RI, USA, pp. 9–16. ZSCC: 0000042.
- Zhu, H. (2019), *kableExtra: Construct Complex Table with 'kable' and Pipe Syntax*. R package version 1.1.0.
URL: <https://CRAN.R-project.org/package=kableExtra>

BIBLIOGRAPHY

Word Count: 12685

A. Environment and Functions

A.1. Session Information

```
Machine:  
[1] "AMD Ryzen 5 2600 Six-Core Processor"  
Num cores:  
[1] 12  
Num threads:  
[1] 12  
RAM:  
33.7 GB  
  
R version 3.6.1 (2019-07-05)  
Platform: x86_64-pc-linux-gnu (64-bit)  
Running under: Manjaro Linux  
  
Matrix products: default  
BLAS: /usr/lib/libopenblas-r0.3.6.so  
LAPACK: /usr/lib/liblapack.so.3.8.0  
  
attached base packages:  
[1] parallel stats      graphics grDevices utils      datasets  methods  
[8] base  
  
other attached packages:  
[1] knitr_1.24            data.table_1.12.2  
[3] showtext_0.7           showtextdb_2.0  
[5] sysfonts_0.8          benchmarkkme_1.0.2  
[7] bibtex_0.4.2          cowplot_1.0.0  
[9] pbapply_1.4-1          rgdal_1.4-4  
[11] future_1.14.0         varhandle_2.0.3  
[13] forcats_0.4.0         stringr_1.4.0  
[15] dplyr_0.8.3           purrr_0.3.2  
[17] readr_1.3.1           tidyverse_1.2.1  
[19] tibble_2.1.3           raster_3.0-2  
[21] lidR_2.1.2             scales_1.0.0  
[23] sp_1.3-1               sf_0.7-7  
[25] kableExtra_1.1.0       magrittr_1.5  
[27] ggpibr_0.2.2           viridisLite_0.3.0  
[29] viridis_0.5.1           RStoolbox_0.2.6  
[31] broom_0.5.2             PerformanceAnalytics_1.5.3  
[33] ggthemes_4.2.0          zoo_1.8-6  
[35] xts_0.11-2              Formula_1.2-3  
[37] Hmisc_4.2-0              lattice_0.20-38  
[39] survival_2.44-1.1       usethis_1.5.1  
[41] devtools_2.1.0           ggplot2_3.2.1  
[43] ENVS450_0.1.0           nvimcom_0.9-83  
[45] pacman_0.5.1            colorout_1.2-1
```

A.2. Functions

A.2.1. Formatting

```
make_table <- function(df, cap = "", dig = 2, col_names = NA, table_env = "table", ...) {
  require(kableExtra)
  require(tidyverse)

  options(knitr.kable.NA = "")
  kable(df,
    digits = dig, caption = cap,
    linesep = "", # remove 5 row spacing
    longtable = FALSE, booktabs = TRUE, # latex opts
    format = "latex",
    escape = F, # allow maths chars
    col.names = col_names,
    table.env = table_env # change to figure*
  ) %>%
  kable_styling(font_size = 9, position = "center") %>%
  row_spec(0, bold = TRUE)
}
```

A.2.2. Catalog to Dataframe

```
ctg_to_df <- function(cluster, aerial = NULL) {
  # read cluster as LAS
  las <- readLAS(cluster)
  # dont read empty clusters
  # all subsequent ctg funcs need these
  if (is.empty(las)) {
    return(NULL)
  }
  # to sp then tibble
  las <- las %>%
    as.spatial()

  if (is.null(aerial) == FALSE){
    las@data$utm <- as.numeric(raster::extract(aerial, las))
  }
  # sp to df
  las <- as.data.frame(las)
  return(las)
}
```

A.2.3. Clip Samples

```
clip_samples <- function(cluster, x) {
  las <- readLAS(cluster)
  if (is.empty(las)) {
    return(NULL)
  }
  # las to sp, sf then spatial join
  las <- las %>%
    as.spatial() %>%
    st_as_sf(las) %>%
    st_set_crs(27700) %>%
    st_join(x)

  # clip points by removing NA values
  las <- las[is.na(las$sample_id) == FALSE, ]
  return(las)
}
```

A.2.4. Filter LAS Noise

```
las_filter_noise <- function(cluster, sensitivity = 1) {
  las <- readLAS(cluster)
  if (is.empty(las)) {
    return(NULL)
  }
```

```

# find 95th quantile intensity values per 10m^2
p95i <- grid_metrics(las, ~ quantile(Intensity, probs = 0.95), 10)
p95z <- grid_metrics(las, ~ quantile(Z, probs = 0.95), 10)
# join by merging
las <- lasmerge spatial(las, p95i, "p95i")
# remove above 95th quantile
las <- lasfilter(las, Intensity < p95i * sensitivity)

las <- lasmerge spatial(las, p95z, "p95z")
# remove above 95th quantile
las <- lasfilter(las, Z < p95z * sensitivity)
# remove unneeded var
las$p95i <- NULL
las$p95z <- NULL
return(las)
}

```

A.2.5. LiDAR Clean

```

lidr_clean <- function(cluster) {
  las <- readLAS(cluster)
  if (is.empty(las)) {
    return(NULL)
  }
  # remove all but last return
  las <- lasfilter(las, NumberOfReturns == ReturnNumber)

  # find ground points
  las <- lasground(las, csf())

  ## Create Point DEM
  # interpolate ground points to create raster dtm. Uses Classification = 2
  # very large number of points, therefore idw used as opposed to kriging
  dtm <- grid_terrain(las, 1, knnidw(k = 10, p = 2))
  # normalise heights using dtm
  las <- lasnormalize(las, dtm)
  return(las)
}

```

A.2.6. Extract Buffer

```

extract_buff <- function(cluster, clip_input) {
  las <- readLAS(cluster)

  if (is.empty(las)) {
    return(NULL)
  }

  # ensure no null input
  if (!is.null(clip_input)) {
    las <- lasclip(las, clip_input)

    # bind clipped inputs together
    # as gives list depending on number of
    # sp objects
    if (length(las) > 1) {
      for (i in 1:length(las)) {
        if (!is.empty(las[[i]])) {
          las <- do.call(rbind, las)
        }
      }
    }
  }
}

```

A.2.7. Find Distances

```

find_dists <- function(x, y) {
  # euclidean distance with sf
}

```

```

d <- st_distance(x, y)
return(d)
}

```

A.2.8. Euclidean Distance

```

# Function to calculate Euclidean distance between 2 points
# using coordinate data
euclidean_distance <- function(p1, p2) {
  return(sqrt((p2[1] - p1[1])**2 + (p2[2] - p1[2])**2))
}

```

A.2.9. Perpendicular Sampling

```

# Function to calculate 2 points on a line perpendicular to another defined by 2 points p1,p2
# For point at interval, which can be a proportion of the segment length, or a constant
# At distance n from the source line
calc_perp <- function(p1, p2, n, interval = 0.5, proportion = TRUE) {
  # Calculate x and y distances
  x_len <- p2[1] - p1[1]
  y_len <- p2[2] - p1[2]

  # If proportion calculate reference point from tot_length
  if (proportion) {
    point <- c(p1[1] + x_len * interval, p1[2] + y_len * interval)
  }
  # Else use the constant value
  else {
    tot_len <- euclidean_distance(p1, p2)
    point <- c(
      p1[1] + x_len / tot_len * interval,
      p1[2] + y_len / tot_len * interval
    )
  }

  # Calculate the x and y distances from reference point
  # to point on line n distance away
  ref_len <- euclidean_distance(point, p2)
  xn_len <- (n / ref_len) * (p2[1] - point[1])
  yn_len <- (n / ref_len) * (p2[2] - point[2])

  # Invert the x and y lengths and add/subtract from the refrence point
  ref_points <- rbind(
    point,
    c(point[1] + yn_len, point[2] - xn_len),
    c(point[1] - yn_len, point[2] + xn_len)
  )

  # Return the reference points
  return(ref_points)
}

```

A.2.10. Combine Catalog

```

comb_ctg <- function(x) {
  las <- readLAS(x)
  if (is.empty(las)) {
    return(NULL)
  }
  return(las)
}

```

A.2.11. Compute Samples

```

# default of 10m increments and 30m width either side of a line
compute_samples <- function(x, increment = 10, width = 30) {
  sample_lines <- c()
  if (nrow(x) > 1) {
    # split linestring into coordinates
  }
}

```

```

road_node <- st_coordinates(x)
tot_len <- 0
len_inc <- increment
len_ofs <- len_inc
# for each linestring "node"
# find dist between them
for (i in 2:nrow(road_node) - 1) {
  n1 <- road_node[i, ]
  n2 <- road_node[i + 1, ]

  len_seg <- euclidean_distance(n1, n2)
  len_ofs <- len_ofs + len_inc

  # max length of linestring
  while (len_ofs <= tot_len + len_seg) {
    len_ofs <- len_ofs + len_inc

    # Add results to output vector
    # for each node of a linestring
    perp_segments <- calc_perp(
      n1, n2, width,
      len_ofs - tot_len,
      proportion = FALSE
    )

    # combine to multipts
    multipoints <- st_multipoint(matrix(perp_segments, ncol = 2))
    pts <- st_cast(st_geometry(multipoints), "POINT")
    n <- length(pts)

    # points to perp lines
    pair <- st_combine(c(pts[1], pts[2], pts[3]))
    # then to linestring + buffer to polygon
    linestring <- st_cast(pair, "LINESTRING") %>%
      st_buffer(2) %>%
      st_sf() %>%
      mutate(road_id = as.character(unique(x$road_id)))
    sample_lines <- rbind(sample_lines, linestring)
  }
  tot_len <- tot_len + len_seg
}
return(sample_lines)
}

```

A.2.12. Greyscale

```

# combine three band rgb
greyscale <- function(x) {
  x <- (x[[1]] + x[[2]] + x[[3]]) / 3
}

```

A.2.13. Compute Individual Linear Model

```

# function to compute individual linear models per
# sample
lm_compute <- function(x, f) tryCatch({
  m <- lm(formula = f, data = x)

  # find p vals
  p <- m %>%
    tidy() %>%
    dplyr::select(p = p.value)

  pred_m <- predict(m, x, type = "response")

  # remove average p val above 0.05
  if (sum(p) / nrow(p) < 0.05) {
    x$lm <- pred_m
  } else {
    x$lm <- NA
  }
})

```

```

}

# find 95th quantiles
x$I_dum <- ifelse(x$lm > quantile(x$lm, .95), 1, 0)

return(x)
}, error = function(e) NULL)
}

```

A.2.14. Filter Returns

```

# remove samples with any road points with a return above 1
filter_returns <- function(x) {
  road <- x[x$road == 1, ]
  if (max(road$NumberOfReturns) == 1) {
    return(x)
  }
}

```

A.2.15. Filter Samples

```

filter_samples <- function(s) {
  # find rows with fewer than 8 samples
  # 8 chosen as ~2m^2 given 25cm res
  if (nrow(s) > 8) {
    # remove outlier points
    # distance based isolation filtering
    distances <- s %>%
      st_distance() %>%
      apply(1, FUN = function(y) {
        min(y[y > 0])
      }) %>%
      as.data.frame() %>%
      mutate(rowid = row_number()) %>%
      select(min_dist = ".", rowid)

    # given min dist between two points
    # remove any above 1m from any other point
    distances <- distances[distances$min_dist < 1, ]

    s <- s %>% mutate(rowid = row_number())

    # remove excluded index values
    s <- s[s$rowid %in% distances$rowid, ]
  }
  return(s)
}

```

A.2.16. Max Dist

```

# two furthest points in a sample
# convert to a linestring to assume max detected road points
max_dist <- function(x) {
  tot_dists <- c()
  # gives largest distances for a collection of pts
  distances <- x %>%
    st_distance(by_element = FALSE) %>%
    unclass() %>%
    "[<"(lower.tri(., diag = TRUE), NA) %>%
    as_tibble() %>%
    rowid_to_column() %>%
    gather(colid, distance, starts_with("V"),
      na.rm = TRUE
    ) %>%
    arrange(desc(distance))

  # use colid to find index of pts with largest distances
  if (nrow(distances) > 0) {
    distances$colid <- gsub("[^0-9.-]", "", distances$colid)
    tot_dists <- rbind(tot_dists, max(distances$distance))
  }
}

```

```

distances <- as.list(distances[1, 1:2]) %>%
  unlist() %>%
  as.numeric()

# convert two pts to linestring
x <- x[distances, ] %>%
  st_combine() %>%
  st_sf() %>%
  st_cast("LINESTRING")
return(x)
}

}

```

A.2.17. Max Lines

```

# combines points filtering and max dist linestrings
# adds linestring length for later
max_lines <- function(x, cents) {
  road_lm <- split(x, f = x$sample_id)

  road_lm <- road_lm %>% compact()

  # filter samples with few points and isolated points >1m
  road_lm <- lapply(road_lm, filter_samples)
  road_lm <- road_lm %>% compact()
  # create linestrings
  road_lm <- lapply(road_lm, max_dist)
  road_lm <- do.call(rbind, road_lm)
  road_lm$length <- as.numeric(st_length(road_lm))
  # find intersecting buffers, ensure intersects centreline
  # prevents lines taller than wide
  road_lm <- st_join(road_lm, cents)

  return(road_lm)
}

```

A.2.18. Mid Points

```

# find mid point between linestring
mid_pts <- function(x) {
  fixed_cents <- st_coordinates(x)[, 1:2]
  x_mid <- mean(fixed_cents[, 1])
  y_mid <- mean(fixed_cents[, 2])
  mid_point <- cbind(x_mid, y_mid)
  mid_point <- as.data.frame(mid_point)
  mid_point <- mid_point %>%
    st_as_sf(coords = c("x_mid", "y_mid"), crs = 27700)
  return(mid_point)
}

```

A.2.19. True Centrelines

```

# using mid points convert a list of mid points into
# linestring, i.e. new road centreline
true_cents <- function(x) {
  rd <- unique(x$road_id)
  y <- x %>%
    distinct()
  n <- nrow(y) - 1
  if (nrow(y) > 2) {
    y <- lapply(X = 1:n, FUN = function(i) {
      pair <- y[c(i, i + 1), ] %>%
        st_combine()
      line <- st_cast(pair, "LINESTRING")
      return(line)
    })
    y <- do.call(c, y)
    # remove some noise through filtering out v large lines
    # optimal was qualitatively assessed
    y <- y[as.numeric(st_length(y)) <

```

```

sum(as.numeric(st_length(y))) / (length(y) / 4)

y <- y %>%
  st_combine() %>%
  st_cast("MULTILINESTRING")
y <- y %>% st_sf()

y <- y[is.na(rd)]

y$road_id <- as.character(rd)
return(y)
}
}

```

A.2.20. Opposite Length

```

# use atan2 to find true width of roads given
# a non perpendicular line, convert to perpendicular to find width
opposite_length <- function(samp, cent) {
  tot_width <- c()
  cent <- cent %>% st_cast("POINT")
  n <- nrow(cent) - 1
  nodelines <- lapply(X = 1:n, FUN = function(i) {
    pair <- cent[c(i, i + 1), ] %>%
      st_combine()
    line <- st_cast(pair, "LINESTRING")
    return(line)
  })
  samp <- samp %>%
    mutate(row_id = row_number())
  samp <- split(samp, samp$row_id)

  for (n in nodelines) {
    for (s in samp) {
      # find which centreline it is associated with
      # as road consist of multiple
      int <- as.numeric(st_crosses(n, s))
      int[is.na(int)] <- 0
      # with correct line, find perpendicular angle
      # and length
      if (int == 1) {
        n1 <- st_coordinates(n)[1, ]
        n2 <- st_coordinates(n)[2, ]
        x <- n1[1] - n2[1]
        y <- n1[2] - n2[2]
        ang_rad <- atan2(x, y)
        ang_deg <- ang_rad * 180 / pi
        if (ang_rad < 0) {
          ang_deg <- ang_deg + 180
        }
        n1 <- st_coordinates(s)[1, ]
        n2 <- st_coordinates(s)[2, ]
        x <- n1[1] - n2[2]
        y <- n1[2] - n2[2]
        ang_rad <- atan2(x, y)
        ang_deg_c <- ang_rad * 180 / pi
        if (ang_rad < 0) {
          ang_deg_c <- ang_deg + 180
        }
        theta <- ang_deg - ang_deg_c
        theta <- theta - 45 # position relative to perp line
        c1_len <- st_length(s)
        # pythagoras to find opposite line length
        opposite <- abs(as.numeric(c1_len) * cos(as.numeric(theta)))
        opposite <- cbind(
          opposite, as.character(unique(cent$road_id)),
          as.character(unique(cent$sample_id)))
      }
    }
  }
}
```

```

        )
        tot_width <- rbind(tot_width, opposite)
    }
}
return(tot_width)
}

```

A.2.21. Model Comparison

```

# find estimated mean widths per road
# remove noise given no road above 8m and below 2m
model_comparison <- function(model) {
  road_lm <- model[!is.na(model$road_id), ]
  rds <- unique(model$road_id)
  road_lm <- split(road_lm, f = road_lm$road_id)

  samp <- Filter(function(x) dim(x)[1] > 0, road_lm)
  cent <- centrelines[centrelines$road_id %in% rds, ]
  cent <- split(cent, f = cent$road_id)
  cent <- Filter(function(x) dim(x)[1] > 0, cent)

  widths <- mapply(opposite_length, samp, cent)
  widths <- do.call(rbind, widths)
  widths <- as.data.frame(widths)

  widths$opposite <- as.numeric(unfactor(widths$opposite))

  widths <- widths[widths$opposite > 2 & widths$opposite < 8, ]

  widths <- widths %>%
    group_by(V2) %>%
    select(road_id = V2, opposite) %>%
    summarise(
      mean_width = mean(opposite)
    )

  return(widths)
}

```

A.2.22. Road Angles

```

# atan2 to find angle between two centreline segments
# relative to previous centreline orientation
road_angles <- function(rd) {
  coords <- rd %>% st_coordinates()
  angle <- c()
  if (nrow(coords) > 1) {
    for (i in 1:(nrow(rd) - 1)) {
      n1 <- coords[i, ]
      n2 <- coords[i + 1, ]
      x <- n1[1] - n2[1]
      y <- n1[2] - n2[2]
      ang_rad <- atan2(y, x)
      ang_deg <- ang_rad / pi * 180

      angle <- append(angle, ang_deg)
      # left of N same as right of N
      angle <- abs(angle)
    }
  }

  # normalise angle, i.e. use prev orientation to find true difference in angle
  normal_ang <- c()
  for (i in 2:length(angle)) {
    # here i - 1 is theta 1, i is theta 2
    normal <- abs(angle[i] - (angle[i - 1]))
    normal_ang <- rbind(normal_ang, normal)
  }
  normal_ang <- cbind(
    normal_ang,

```

```
    as.character(rep(unique(rd$road_id), nrow(normal_ang)))
)
return(normal_ang)
}
```

A.2.23. Height Change

```
# find difference in average height between two samples
height_change <- function(x) {
  elev <- c()
  samples <- split(x, x$sample_id)
  if (length(samples) > 2) {
    for (s in 2:length(samples) - 1) {
      pair <- samples[c(s, s + 1)]
      n1 <- mean(pair[[1]]$Z)
      n2 <- mean(pair[[2]]$Z)
      e <- abs(n1 - n2)
      e <- cbind(
        as.character(unique(samples[[s]]$road_id)), e
      )
      elev <- rbind(elev, e)
    }
  }
  return(elev)
}
```

B. Additional Tables and Figures

```
Error in kable(df, digits = dig, caption = cap, linesep = "", longtable = FALSE, :  
object 'corResults' not found
```

Table B.1: *Estimated number of bends per road*

Road ID	Number of Bends	Road Length (km)	Bends per Kilometer
6	8	0.36	22.29
8	4	0.19	20.79
5	2	0.11	18.77
9	4	0.21	18.68
7	4	0.26	15.34
36	4	0.28	14.27
38	1	0.07	13.34
14	3	0.24	12.59
32	3	0.24	12.42
2	4	0.38	10.57
21	1	0.11	9.05
4	3	0.38	7.94
12	2	0.25	7.93
39	1	0.13	7.82
31	1	0.13	7.74
15	1	0.13	7.58
10	2	0.26	7.58
33	4	0.54	7.37
13	1	0.17	5.96
17	1	0.18	5.62
30	2	0.41	4.85
34	1	0.21	4.85
25	1	0.23	4.36
24	1	0.24	4.16
1	1	0.24	4.15
18	2	0.74	2.70
16	0	0.18	0.00
20	0	0.07	0.00
40	0	0.08	0.00
41	0	0.08	0.00

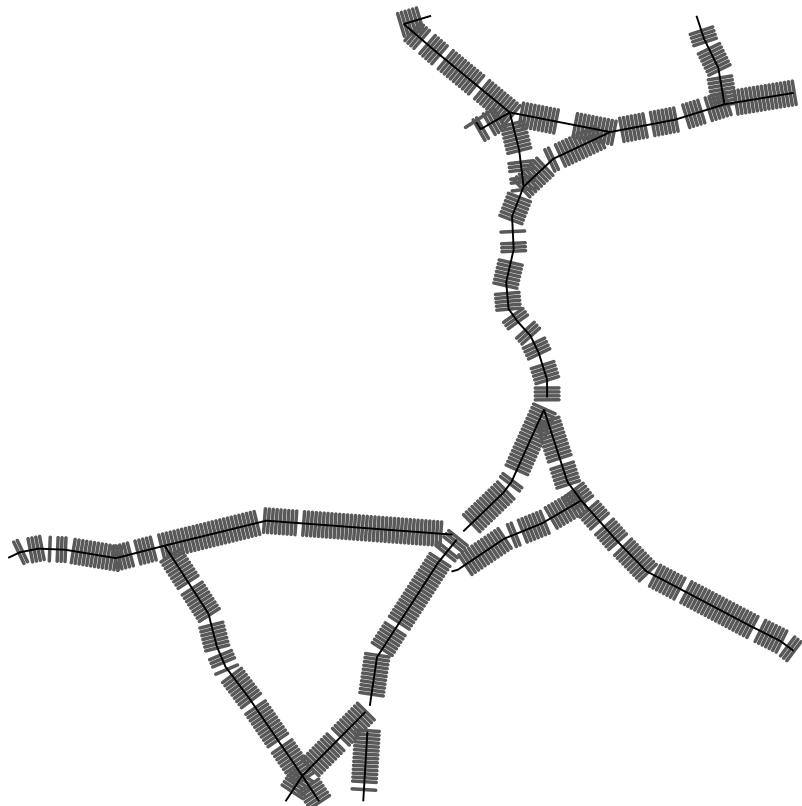


Fig. B.1: Sample lines extracted based on known road locations

C. Scripts

C.1. Clean Data

```
# Source Scripts
source("./functions.r")

# Create las catalog with all .laz files
ctg <- catalog("../data/point/")
opt_chunk_size(ctg) <- 500
opt_chunk_buffer(ctg) <- 20

# create lax file to index + speed up process
plan(multisession, workers = 6L)
set_lidr_threads(12L)
# speed up lax computation time
lidR:::catalog_laxindex(ctg)

# ctg to points csv
las <- catalog_apply(ctg, ctg_to_df)
las <- do.call(rbind, las)
las <- las %>%
  select(-c(
    Synthetic_flag,
    Keypoint_flag,
    Withheld_flag
  ))

fwrite(las, "../data/point/points.csv")

# filter using sql expressions why not
# very very slow to read in full gpkg, don't run unless new data added
#roads <- st_read("../data/osroads/oproad_gpkg_gb/data/oproad_gb.gpkg",
#  layer = "RoadLink", query =
#    "SELECT * FROM RoadLink WHERE
#      formOfWay = \"Single Carriageway\" AND
#      roadFunction <> \"Restricted Local Access Road\" "
#) %>%
#  st_zm() # remove z axis
#
#roads <- as_Spatial(roads)
#roads <- raster::crop(roads, as.matrix(extent(ctg))) %>%
#  st_as_sf()

#st_write(roads, "../data/osroads/oproad_crop.gpkg")

roads <- st_read("../data/osroads/oproad_crop.gpkg") %>%
  mutate(
    len = as.numeric(st_length(geom)),
    road_id = paste0("road_", row_number())
  ) %>%
  select(c(road_id, roadFunction, len, geom)) %>%
  subset(len > 50)

# keep line polys
roads_line <- roads

# one buffer to include non road points, 1m buffer to show only road points
roads_buff <- st_buffer(roads, 30)
roads <- st_buffer(roads, 1)
roads_buff_union <- st_union(roads_buff)
```

```

# write all outputs to files
st_write(roads, "../data/derived/roads/roads.gpkg",
    delete_layer = TRUE
)
st_write(roads_line, "../data/derived/roads/roads_line.gpkg",
    delete_layer = TRUE
)
st_write(roads_buff, "../data/derived/roads/roads_buff.gpkg",
    delete_layer = TRUE
)

st_write(roads_buff_union, "../data/derived/roads/roads_buff_diss.gpkg",
    delete_layer = TRUE
)

roads_buff <- st_read("../data/derived/roads/roads_buff.gpkg") %>%
    as_Spatial()

ctg <- catalog("../data/point/")
opt_output_files(ctg) <- "../data/derived/ctg_clean/{ID}_clean"
opt_chunk_size(ctg) <- 500
opt_chunk_buffer(ctg) <- 20
catalog_apply(ctg, lidr_clean)

ctg <- catalog("../data/derived/ctg_clean/")
opt_output_files(ctg) <- "../data/derived/ctg_buff/{ID}_tile"
opt_chunk_size(ctg) <- 500
opt_chunk_buffer(ctg) <- 20
catalog_apply(ctg, extract_buff, roads_buff)

ctg <- catalog("../data/derived/ctg_buff/")
opt_output_files(ctg) <- "../data/derived/ctg/{ID}_tile"
opt_chunk_size(ctg) <- 500
opt_chunk_buffer(ctg) <- 20
catalog_apply(ctg, las_filter_noise, sensitivity = 1.2)

# non normalised ctg
ctg_notnorm <- catalog("../data/point/")
opt_output_files(ctg_notnorm) <- "../data/derived/ctg_notnorm/{ID}_tile"
opt_chunk_size(ctg_notnorm) <- 500
opt_chunk_buffer(ctg_notnorm) <- 20
catalog_apply(ctg_notnorm, extract_buff, roads_buff)

# read in written roads file
roads <- read_sf("../data/derived/roads/roads.gpkg")

# find roads extent shows study area + used for aerial imagery from digimaps
extent <- st_as_sfc(st_bbox(roads))

# Write extent shapefile
st_write(extent, "../data/derived/extent.extent.gpkg", delete_layer = TRUE)

```

C.2. Create Sample lines

```

source("./functions.r")

centrelines <- read_sf("../data/derived/roads/roads_line.gpkg") %>%
    st_set_crs(27700)

roads_split <- centrelines %>% st_cast("POINT")

roads_split <- split(roads_split, f = roads_split$road_id)

sample_lines <- lapply(roads_split, compute_samples)
sample_lines <- do.call(rbind, sample_lines)

sample_lines <- sample_lines %>%
    st_set_crs(27700)
# label each sample
sample_lines$sample_id <- seq.int(nrow(sample_lines))

```

```

write_sf(sample_lines, ".../data/derived/roads/sample_lines.gpkg")

ctg <- catalog(".../data/derived/ctg_buff/")

opt_chunk_size(ctg) <- 500
plan(multisession, workers = 6L)
set_lidr_threads(12L)

# remove points outside samples
comb <- catalog_apply(ctg, clip_samples, sample_lines)
comb <- comb <- do.call(rbind, comb)

roads <- st_read("../data/derived/roads.roads.gpkg") %>%
  st_transform(27700)
roads_df <- roads %>% st_drop_geometry()

comb <- comb %>%
  st_transform(27700)

joined_output <- merge(comb, roads_df, by = "road_id")

int <- st_contains(roads, joined_output, sparse = FALSE) %>%
  colSums()

joined_output$road <- int

# turn to binary, some road buffers overlap
joined_output$road <- as.numeric(joined_output$road > 0)

# aerial data
jpgs <- Sys.glob("../data/aerial/*.jpg")
jpgs <- lapply(jpgs, brick)
grey_rasters <- lapply(jpgs, greyscale)
grey_rasters <- lapply(grey_rasters, brick)
aerial <- do.call(merge, grey_rasters)
aerial <- crop(aerial, roads)

writeRaster(aerial, ".../data/derived/aerial/aerial_crop.tif",
  format = "GTiff", overwrite = TRUE
)

# crop aerial data
lum <- raster::extract(aerial, joined_output)
joined_output$lum <- as.numeric(lum)

# find dists from centrelines
joined_output <- split(joined_output, f = joined_output$road_id)
centrelines <- split(centrelines, centrelines$road_id)

centrelines <- centrelines[names(joined_output)]

dists <- mapply(
  find_dists,
  joined_output,
  centrelines
)

joined_output <- do.call(rbind, joined_output)
dists <- do.call(rbind, dists)
joined_output$dists <- dists

coords <- joined_output %>%
  st_coordinates()

# change to data.frame
joined_output <- joined_output %>%
  st_drop_geometry() %>%
  mutate(
    X = coords[, 1],
    Y = coords[, 2]
  )

```

```
fwrite(joined_output, ".../data/derived/model_data/sampled_las.csv")
```

C.3. Linear Models and Improve Centrelines

```
source("./functions.r")
sampled_las <- fread("../data/derived/model_data/sampled_las.csv")

# ground pts only
sampled_las <- sampled_las[sampled_las$Classification == 2, ]

# global linear model: unfiltered
# for this section see social survey + ss assessment 2
f1 <- as.formula("road ~ Intensity + lum + dists + Z + NumberOfReturns")
lm1 <- lm(data = sampled_las, formula = f1)
lm1_pred <- predict(lm1, sampled_las, type = "response")

sampled_las$lm1_pred <- lm1_pred
sampled_las$lm1_dum <- ifelse(sampled_las$lm1_pred >
    quantile(sampled_las$lm1_pred, .95), 1, 0)

sampled_las$lm1_pred <- lm1_pred
sampled_las$lm1_dum90 <- ifelse(sampled_las$lm1_pred >
    quantile(sampled_las$lm1_pred, .90), 1, 0)

sampled_las$lm1_pred <- lm1_pred
sampled_las$lm1_dum80 <- ifelse(sampled_las$lm1_pred >
    quantile(sampled_las$lm1_pred, .80), 1, 0)

fwrite(sampled_las, ".../data/derived/model_data/linearmodels.csv")
```

C.4. Road Widths

```
source("./functions.r")
## ---- widths
road_lm <- fread("../data/derived/model_data/linearmodels.csv") %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)

roads <- st_read("../data/derived/roads/roads_line.gpkg")
roads_5m <- st_read("../data/derived/roads/roads_line.gpkg") %>%
  st_buffer(5)

road_lm90 <- road_lm[road_lm$lm1_dum90 == 1, ]
# find improved centrelines
fixed_cents <- list(
  road_lm90
)

# includes all filtering, max dist points
fixed_cents <- lapply(fixed_cents, max_lines, cents = roads)

fixed_cents <- do.call(rbind, fixed_cents)
fixed_cents <- fixed_cents %>%
  mutate(rowid = row_number())

mid_point <- split(fixed_cents, fixed_cents$rowid)
mid_points <- lapply(mid_point, mid_pts)

mid_points <- do.call(rbind, mid_points)
mid_points <- mid_points %>%
  st_join(roads_5m)
mid_rds <- split(mid_points, mid_points$road_id)

# remove empty geoms
mid_rds <- Filter(function(x) dim(x)[1] > 0, mid_rds)
cents <- lapply(mid_rds, true_cents)
cents <- compact(cents)
cents <- do.call(rbind, cents)
```

```

st_write(cents, "../data/derived/roads/cent_iteration1.gpkg",
  layer_options = "OVERWRITE=yes"
)

## ---- angles
roads_split <- st_read("../data/derived/roads/roads_line.gpkg") %>%
  st_cast("POINT") %>%
  st_set_crs(27700)

roads_split <- split(roads_split, roads_split$road_id)

angles <- lapply(roads_split, road_angles)
angles <- do.call(rbind, angles)
row.names(angles) <- NULL
angles <- angles %>%
  as.data.frame()
names(angles) <- c("angle", "road_id")
angles$angle <- as.numeric(unfactor(angles$angle))

angles <- angles %>%
  group_by(road_id) %>%
  summarise(
    mean_angle = mean(angle),
    max_angle = max(angle)
  )

roads <- merge(roads, angles, by = "road_id")

## ---- heights
# Non-normalised las files
sample_lines <- st_read("../data/derived/roads/sample_lines.gpkg") %>%
  st_set_crs(27700)
roads_1m <- st_read("../data/derived/roads/roads.gpkg")
ctg <- catalog("../data/derived/ctg_notnorm/")
opt_chunk_size(ctg) <- 500
plan(multisession, workers = 6L)
set_lidr_threads(12L)

# remove points outside samples
las_rds <- catalog_apply(ctg, clip_samples, sample_lines)
las_rds <- do.call(rbind, las_rds)

las_rds <- las_rds[las_rds$NumberOfReturns == 1 &
  las_rds$Classification == 2, ]

rds <- st_read("../data/derived/roads/roads.gpkg") %>%
  st_transform(27700)

rd_line <- st_read("../data/derived/roads/roads_line.gpkg", quiet = TRUE) %>%
  mutate(len = as.numeric(st_length(geom))) %>%
  select(c(road_id, len)) %>%
  st_drop_geometry()

roads_df <- rds %>% st_drop_geometry()

las_rds <- las_rds %>%
  st_transform(27700)

las_rds <- merge(las_rds, roads_df, by = "road_id")

int <- st_contains(roads_1m, las_rds, sparse = FALSE) %>%
  colSums()

las_rds$road <- int

# remove overlapping road points
las_rds <- las_rds[las_rds$road < 2, ]
# turn to binary (might not be needed)
las_rds$road <- as.numeric(las_rds$road > 0)

las_rds <- las_rds[las_rds$road == 1, ]

```

```

las_rds <- split(las_rds, las_rds$sample_id)

las_rds <- lapply(las_rds, filter_returns)

las_rds <- las_rds %>%
  compact()

las_rds <- do.call(rbind, las_rds)

las_height <- split(las_rds, las_rds$road_id)

las_height <- lapply(las_height, height_change)

las_height <- do.call(rbind, las_height)
las_height <- as.data.frame(las_height)

names(las_height) <- c("road_id", "Z")
las_height <- las_height %>%
  merge(rd_line, by = "road_id")

las_height <- las_height %>%
  group_by(road_id) %>%
  summarise(
    tot_z = sum(as.numeric(unfactor(Z))) / (mean(len) / 1000),
  ) %>%
  drop_na()

roads <- merge(roads, las_height, by = "road_id")

## ---- surface_qual
las_qual <- las_rds %>%
  group_by(road_id) %>%
  summarise(
    mean_int = mean(Intensity),
    range_int = max(Intensity) - min(Intensity)
  ) %>%
  drop_na() %>%
  select(c(road_id, mean_int, range_int))

roads <- merge(roads, las_qual, by = "road_id") %>%
  st_drop_geometry()

write.csv(roads, "../data/final_data/final.csv")

```

C.5. Improved Centreline Models

```

source("./functions.r")
cent1 <- st_read("../data/derived/roads/cent_iteration1.gpkg") %>%
  st_transform(27700)
sampled_las <- fread("../data/derived/model_data/sampled_las.csv") %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)
aerial <- raster("../data/derived/aerial/aerial_crop.tif")

# improved roads centrelines
roads <- cent1 %>%
  st_buffer(2)

roads_df <- roads %>% st_drop_geometry()

joined_output <- merge(sampled_las, roads_df, by = "road_id")

int <- st_contains(roads, joined_output, sparse = FALSE) %>%
  colSums()

joined_output$road <- int

# turn to binary, some road buffers overlap
joined_output$road <- as.numeric(joined_output$road > 0)

```

```

# crop aerial data
lum <- raster::extract(aerial, joined_output)
joined_output$lum <- as.numeric(lum)

# find dists from centrelines
joined_output <- split(joined_output, f = joined_output$road_id)
centrelines <- split(cent1, cent1$road_id)

centrelines <- centrelines[names(joined_output)]

dists <- mapply(
  find_dists,
  joined_output,
  centrelines
)

joined_output <- do.call(rbind, joined_output)
dists <- do.call(rbind, dists)
joined_output$dists <- dists

coords <- joined_output %>%
  st_coordinates()
cent1_las <- joined_output %>%
  st_drop_geometry() %>%
  mutate(
    X = coords[, 1],
    Y = coords[, 2]
  )

fwrite(cent1_las, "../data/derived/model_data/cent1_lm.csv")

# linear models with improved centrelines
# for this section see social survey + ss assessment 2
f1 <- as.formula("road ~ Intensity + lum + dists + Z + NumberOfReturns")
lm1 <- lm(data = cent1_las, formula = f1)
lm1_pred <- predict(lm1, cent1_las, type = "response")

f2 <- as.formula("road ~ Intensity + dists + Z + NumberOfReturns")
lm2 <- lm(data = cent1_las, formula = f2)
lm2_pred <- predict(lm2, cent1_las, type = "response")

cent1_las$lm1_pred <- lm1_pred
cent1_las$lm1_dum <- ifelse(cent1_las$lm1_pred >
  quantile(cent1_las$lm1_pred, .95), 1, 0)

cent1_las$lm2_pred <- lm2_pred
cent1_las$lm2_dum <- ifelse(cent1_las$lm2_pred >
  quantile(cent1_las$lm2_pred, .95), 1, 0)

# individual linear probability model: has to filter out canopy: proof of concept
cent1_las <- split(cent1_las, cent1_las$sample_id)
cent1_las <- lapply(cent1_las, filter_returns)
f1 <- as.formula("road ~ Intensity + dists + Z + NumberOfReturns")
cent1_las <- lapply(cent1_las, lm_compute, f = f1)
cent1_las <- do.call(rbind, cent1_las)

fwrite(cent1_las, "../data/final_data/cent_lm.csv")

lmi <- cent1_las[cent1_las$I_dum == 1, ] %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)
lm1 <- cent1_las[cent1_las$lm1_dum == 1, ] %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)
lm2 <- cent1_las[cent1_las$lm2_dum == 1, ] %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)

lm2 <- split(lm2, lm2$road_id)
tot_pts <- lapply(lm2, function(x) {
  tot_pts <- nrow(x)
  return(tot_pts)
})

```

```

})
lm2 <- do.call(rbind, lm2)

lm_max_widths <- list(lmi, lm1, lm2)

road_buff <- st_read("../data/derived/roads/roads_buff.gpkg")

centrelines <- do.call(rbind, centrelines)
# includes all filtering, max dist points
lm_max_widths <- lapply(lm_max_widths, max_lines, cents = centrelines)

lm_max_widths <- lapply(lm_max_widths, function(x) {
  x <- x[x$length < 8 & x$length > 2, ]
  x <- x[!is.na(x$road_id), ]
})

# save lines for comparison
for (i in 1:length(lm_max_widths)) {
  st_write(lm_max_widths[[i]], paste0("../data/final_data/widths_", i, ".gPKG"),
    layer_options = "OVERWRITE=YES"
  )
}

#####
centrelines <- st_read("../data/derived/roads/cent_iteration1.gPKG")
linear_widths <- lapply(lm_max_widths, model_comparison)
linear_widths <- linear_widths %>%
  reduce(left_join, by = "road_id")

names(linear_widths) <- c(
  "road_id",
  "lmi_mean",
  "lm1_mean",
  "lm2_mean"
)
tot_pts <- do.call(rbind, tot_pts) %>%
  as.data.frame() %>%
  rownames_to_column()
names(tot_pts) <- c("road_id", "tot_pts")

linear_widths <- merge(linear_widths, tot_pts, by = "road_id")

roads <- fread("../data/final_data/final.csv")

roads <- merge(roads, linear_widths, by = "road_id")

#####
# old centrelines
sampled_las <- fread("../data/derived/model_data/sampled_las.csv") %>%
  as.data.frame() %>%
  st_as_sf(coords = c("X", "Y"), crs = 27700)

f1 <- as.formula("road ~ Intensity + lum + dists + Z + NumberOfReturns")
lm0 <- lm(data = sampled_las, formula = f1)
lm0_pred <- predict(lm0, sampled_las, type = "response")
sampled_las$lm0_pred <- lm0_pred
sampled_las$lm0_dum <- ifelse(sampled_las$lm0_pred >
  quantile(sampled_las$lm0_pred, .95), 1, 0)

fwrite(sampled_las, "../data/final_data/lm0.csv")

lm0 <- sampled_las[sampled_las$lm0_dum == 1, ]

lm_max_widths <- list(lm0)

road_buff <- st_read("../data/derived/roads/roads_buff.gPKG")
centrelines <- st_read("../data/derived/roads/roads_line.gPKG")
# includes all filtering, max dist points
lm_max_widths <- lapply(lm_max_widths, max_lines, cents = centrelines)

lm_max_widths <- lapply(lm_max_widths, function(x) {

```

```
x <- x[x$length < 8 & x$length > 2, ]
x <- x[!is.na(x$road_id), ]

# save lines for comparison
st_write(lm_max_widths[[1]], paste0("../data/final_data/widths_0.gpkg"),
  layer_options = "OVERWRITE=YES"
)

#####
linear_widths <- lapply(lm_max_widths, model_comparison)
linear_widths <- linear_widths %>%
  reduce(left_join, by = "road_id")

names(linear_widths) <- c(
  "road_id",
  "lm0_mean"
)

roads <- merge(roads, linear_widths, by = "road_id")
fwrite(roads, "../data/final_data/final.csv")

# aerial data

# ctg to points csv
ctg <- catalog("../data/derived/ctg/")
las <- catalog_apply(ctg, ctg_to_df, aerial)
las <- do.call(rbind, las)
las <- las %>%
  select(-c(
    Synthetic_flag,
    Keypoint_flag,
    Withheld_flag
  ))

fwrite(las, "../data/point/points_clean.csv")
```