Nottingham Geospatial Institute

RURAL IMPLEMENTATION OF CONNECTED, AUTONOMOUS AND ELECTRIC VEHICLES

By

Joseph George Walters

MEng (Hons)

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ABSTRACT

Connected, autonomous and electric vehicles (CAEV) are at the forefront of transport development. They are intended to provide efficient, safe and sustainable transport solutions to solve everyday transport problems including congestion, accidents and pollution. However, despite significant industry and government investment in the technology, little has been done in the way of exploring the implementation of CAEVs in rural scenarios. This thesis investigates the potential for rural road CAEV implementation in the UK. In this work, the rural digital and physical infrastructure requirements for CAEVs were first investigated through physical road-based experimentation of CAEV technologies. Further investigations into the challenges facing the rural implementation of CAEVs were then conducted through qualitative consultations with transport planning professionals. Quantitative and qualitative analysis of these investigations revealed a need for better rural infrastructure, and an overall lack of understanding regarding CAEVs and their rural implementation requirements amongst the transport planning industry. The need for a measurement tool for transport planners was identified, to expose the industry to, and educate them about, CAEVs and their rural potential. As a result, a CAEV Rural Transport Index (CARTI) is proposed as a simple measurement tool to assess the potential for rural CAEV implementation. The CARTI was implemented, and its effectiveness tested, through further consultation with transport planning professionals. The results indicate the potential for the CARTI to be used as a component of decision-making processes at both local authority and national levels. In conclusion, effective rural CAEV implementation relies on transport planners having a strong understanding of rural community transport needs, the solutions CAEV technologies can offer and the supporting infrastructure they require. Further, the CARTI was found to be an effective tool to support the development of this required understanding and recommendations have therefore been made for its future development.

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LIST OF ABBREVIATIONS

ABS	Anti-lock Brakes
ADAS	Advanced Driver-Assistance Systems
AHS	Automated Highway Systems
AV	Autonomous Vehicle
AVRI	Autonomous Vehicle Readiness Index
BDU	BeiDou (China, Satellite Positioning System)
BEIS	(Department for) Business, Energy, and Industrial Strategy
BEV	Battery-Electric Vehicle
BIM	Building Information Model
BSI	British Standards Institute
BSM	Basic Safety Message
CAEV	Connected, Autonomous and Electric Vehicle
CAP	Commonwealth Association of Planners
CARTI	CAEV Rural Transport Index
CAV	Connected and Autonomous Vehicle
CCAV	Centre for Connected and Autonomous Vehicles
CPD	Continued Professional Development
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease
CV	Connected Vehicle
C-V2X	Cellular Vehicle to Everything
DARPA	Defense Advanced Research Projects Agency
DfT	Department for Transport

DLUHC	Department for Levelling Up, Housing and Communities (previously MHCLG)
DRT	Demand Responsive Transport
DSRC	Dedicated Short-Range Communication
DTG	Doctoral Training Grant
ELASTIC	Evaluative and Logical Approach to Sustainable Transport Indicator Compilation
EPSRC	Engineering and Physical Sciences Research Council
EV	Electric Vehicle
FCEV	Fuel-Cell Electric Vehicle
FoRMS	Future of Rural Mobility Study
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GLONASS	Global Navigation Satellite System (Russia)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (USA)
GTFS	General Transit Feed Specification (data type)
HDI	Human Development Index
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IOT	Internet of Things
IQR	Interquartile Range
IRP	Integrated Rail Plan
ITF	International Transport Forum
KPMG	Klynveld Peat Marwick Goerdeler
LDNP	Lake District National Park

LDNPA	Lake District National Park Authority
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LOS	Line Of Sight
LSOA	Lower Layer Super Output Areas
LTE	Long-Term Evolution
MaaS	Mobility as a Service
MCDA	Multi-Criteria Decision Aid
MHCLG	Ministry of Housing, Communities & Local Government
MPI	Multidimensional Poverty Index
NGI	Nottingham Geospatial Institute
NRTK	Network Real-Time Kinematic
ONS	Office for National Statistics
PDNP	Peak District National Park
PDNPA	Peak District National Park Authority
POD	Pod On Demand (developed by Westfield Technology Group)
P&DL	Peaks and Dales Line
RAC	Royal Automobile Club
RB	Resource Block
RE	Resource Element
RIN	Royal Institute of Navigation
RSN	Rural Services Network
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RTK	Real-Time Kinematic
RYR	Restore Your Railways

SAE	Society for Automotive Engineers
SAM	Sustainable Accessibility and Mobility framework
SDF	Social Development Framework
SDG	Sustainable Development Goal
SRITC	Scottish Rural and Islands Transport Community
TfL	Transport for London
TPS	Transport Planning Society
UAV	Unmanned Aerial Vehicle
UN	United Nations
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
WEF	World Economic Forum
WTO	World Trade Organisation

INTRODUCTION

Agricultural activity has defined rural characteristics for many years resulting in a lack of development and an ignorance of rural social issues (Abreu et al., 2019, Rodrigue and Notteboom, 2020). However, the economic, social and environmental structures of rural working communities are becoming more diverse (Abreu et al., 2019, Michalek and Zarnekow, 2012b), with continuing trends of counter-urbanisation, particularly in the wake of COVID-19, highlighting the increasing appeal of rural community life (Bosworth, 2010, Hansen and Aner, 2017, Stockdale, 2014). Despite this, the continuous migration of young people from rural areas to more rewarding urban employment opportunities leaves aging rural populations. The Future of Rural Mobility study finds that in the Midlands region of the UK, 24% of the rural population is over 65, compared to 16% in urban areas (Midlands Connect, 2020a).

Compared with urban communities, rural communities generally have higher levels of poverty, social exclusion and inequality, which can be directly linked to physical isolation and a lack of accessibility due to scattered and peripheral rural characteristics (Abreu et al., 2019, Bosworth et al., 2020, Lucas et al., 2016, Roberts et al., 2006, Velaga et al., 2012, Vitale Brovarone and Cotella, 2020). Improving accessibility is therefore fundamental to the development of transport solutions and the rural socio-economic systems they serve (Cheng et al., 2007, Vitale Brovarone and Cotella, 2020). Transport enables mobility to ensure access to markets and resources which promotes economic and social growth, improves access to public services and opportunities, reduces social exclusion and improves quality of life (Rodrigue and Notteboom, 2020, Whitelegg et al., 2010). A more detailed literature review of rural transport challenges can be found in Chapter 1.

As described, transportation is fundamental to socioeconomic systems which rely on the mobility of people and goods to be sustained and developed. However, sustaining and developing transport infrastructure is a continuous challenge (Rodrigue, 2020a, Rodrigue and Notteboom, 2020). Intelligent Transport Systems and Services (ITSS) are being developed to solve the challenges of increasing transport demand and emissions. They aim to make transport solutions safer, more efficient, and therefore, more sustainable, whilst reducing the need for increasingly unviable hard infrastructure solutions (Armitage, 2019, European Commission, 2017, Wyllie, 2019).

Among the most researched ITSS and automotive technologies are Connected, Autonomous and Electric Vehicles (CAEV) (Vdovic et al., 2019). Across research and in the media, the terms Autonomous Vehicle (AV), Connected and Autonomous Vehicle (CAV) and CAEV are generally used interchangeably. For example, Transport for London (TfL) defines a CAV as either a connected or autonomous vehicle, or both, despite the terms CV and AV being used elsewhere to specifically distinguish between the two (Transport for London, 2020). In the USA however, the term AV appears to be an umbrella terms that includes CAV research and development (Federal Highway Administration, 2020).

At the very least, in most cases, all three refer to autonomous vehicles conforming to the varying levels of autonomy as defined by the Society of Automotive Engineers (SAE) (SAE, 2021). This is because AV's began as a concept and have rapidly progressed over the past decade to incorporate communication technologies and electric powertrains, hence the terms CAV and CAEV becoming more appealing (Vaidya and Mouftah, 2020).

Chapter 2 describes the technological elements of CAEVs in more detail, and Figure 2.1 defines the six levels of autonomy. In summary CAEVs are complex systems combining AV, CV and Electric Vehicle (EV) technologies. Vaidya and Mouftah (2020) and Vdovic (2019) recognise five distinct components of CAEVs:

- A perception system responsible for sensing and understanding its surroundings using technologies including Radar, LiDAR and cameras;

- Localisation and mapping systems most commonly using GNSS to provide positioning;

- Software containing decision-making algorithms enabling the vehicle to negotiate hazards and follow standard driving rules;

- A communication system enabling V2X capabilities through wireless communication links;

- An energy storage system including charging and battery technologies.

Throughout this thesis, primary discussions centre around automated road-based transport solutions which require effective connectivity to realistically meet desired safety and efficiency needs. With EV technologies increasingly popular, and their capabilities to seamlessly integrate AV and CV technologies together, the term CAEV will be used throughout this thesis. It is assumed that any future rural transport implementations based on, or in line with, this research, will ultimately rely on CAEV technologies, across any of the SAE's six levels of autonomy (Figure 2.1). References to the other terminologies may be made, particularly when discussing external projects or when reviewing literature that does not include the term CAEV.

CAEVs have the potential to provide effective and sustainable transport solutions that are capable of addressing many of the rural transport problems explored in this thesis. For example, replacing, or supplementing, traditional public transport with alternative options such as demand responsive transport (DRT) can improve rural accessibility in a sustainable way (Vitale Brovarone and Cotella, 2020, Lakatos et al., 2020, Dianin et al., 2021).

Real-time vehicle positioning, dynamic connectivity and dynamic mapping are the three key technologies required for the successful development of CAEV transport. These technologies must be reliable, accurate and continuously available if CAEVs are to be an effective transport solution and will require appropriate supporting infrastructure (Stephenson et al., 2013a). In rural areas, the provision of this infrastructure can be challenging. Wireless connectivity in terms of 4G signals and the consistent readability of roads are two of the main infrastructural challenges facing rural CAEV implementation (SMMT, 2017). In addition, despite the high accuracies of network real-time kinematic (NRTK) satellite positioning, it lacks availability when line of sight is interrupted, which is of particular concern on unpredictable and poorer quality rural roads (Aponte et al., 2014, Yang et al., 2010).

Despite the challenges, studies on CAEV implementation in rural communities and on rural roads is limited, with much of the literature focused on urban CAEV implementation and associated infrastructure challenges. The theme of urban bias concerning transport and digital infrastructure provision is an important and prominent theme throughout this thesis.

Aims, Objectives and Contributions to Knowledge

The aim of this thesis is to assess and promote the potential of CAEVs to contribute to sustainable rural transport development. To achieve this aim, the following research objectives have been explored:

A. Assess the relationships between rural transport development and CAEV development within the context of sustainable transport development;

B. Determine to what extent the needs of rural areas can be met by CAEV systems and technologies;

C. Identify the practical challenges of CAEV implementation;

D. Set out the requirements for rural CAEV implementation where there is distinguishable need and capacity;

E. Contribute to the rural implementation of CAEV systems and technologies.

Therefore, this thesis is a contribution to knowledge in the area of rural CAEV development and implementation. There are four distinguishable project stages described in this thesis, each of which makes its own individual contribution to knowledge. Figure 0.1 summarises the investigative processes and contributive procedures described in this thesis to meet the research aim and objectives.

- Exploration of rural transport challenges and the potential for CAEVs to contribute to these challenges;

- Investigations into digital and physical infrastructure requirements for rural CAEV implementation;

- Determination of the state and readiness of the transport planning industry, and investigation into professional transport planner perspectives regarding rural CAEV implementation;

- Development and assessment of a CAEV Rural Transport Index (CARTI) to support transport planner decision-making regarding rural CAEV implementation.

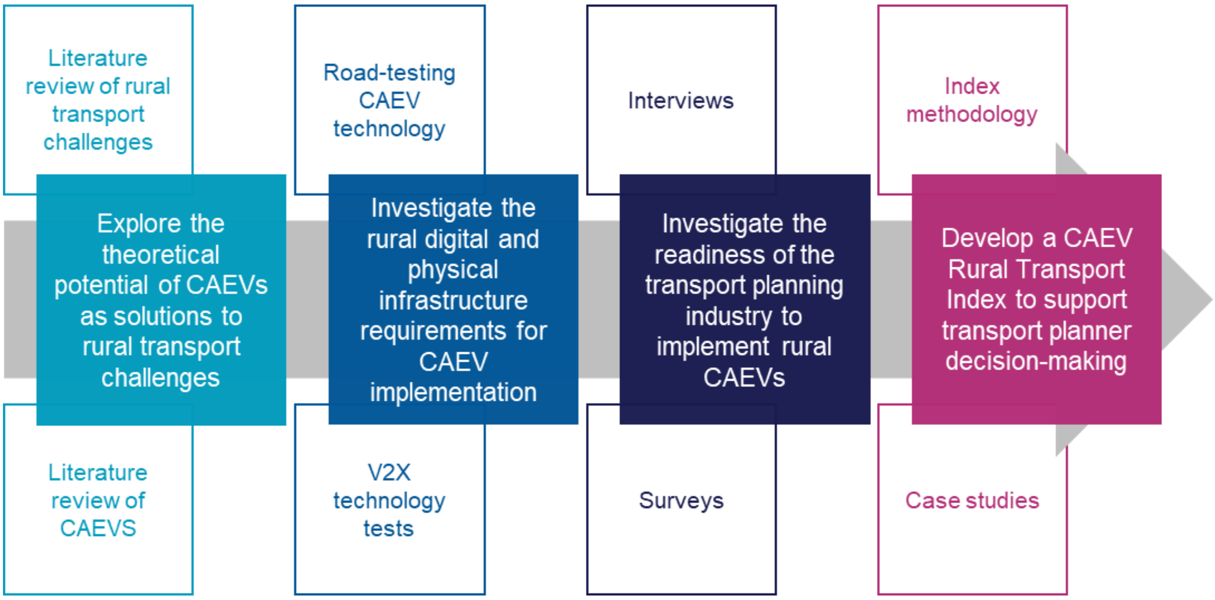


Figure 0.1 Investigative research process and stages

Thesis Structure

This thesis consists of a total of seven chapters with appendices structured in a logical order.

In Chapter 1 a literature review has been conducted exploring the current state of rural transportation and its development as well as rural transport systems and infrastructure challenges in rural regions of the UK.

Chapter 2 reviews the literature regarding the concepts and history behind CAEVs as well as bringing together the latest state of the art information on CAEV technologies and infrastructure requirements. Referring to Chapter 1, Chapter 2 also explores whether, and to what extent, CAEVs have the potential to contribute as solutions to rural transport challenges.

Chapter 3 describes a number of experimental investigations into some of the technological and infrastructural challenges facing CAEV implementation in specifically rural areas of the UK. These were conducted in real environments on the ground and on roads using satellite positioning and terrestrial communication technologies. Chapter 3 also contains an additional literature review of non-technological challenges including an exploration of the state and importance of the role of transport planners in rural CAEV implementation.

Chapter 4 describes the development of an elicitation methodology which was then used to conduct surveys and interviews with transport planning professionals to gauge their understanding of, and capacity to support, rural CAEV implementation. The results from both survey and interviews were analysed and discussed with reference to three research questions that are defined in the chapter. This chapter concludes with a hypothesis that suggests a need for a rural CAEV assessment tool to aid transport planners in the delivery of effective CAEV solutions in rural areas.

Chapter 5 proposes the CAEV Rural Transport Index (CARTI) and discusses the development of a methodology from which the CARTI is created. The methodology is described in stages which are performed throughout the chapter. Chapter 5 concludes with the selection of the six indicators which form the completed CARTI.

Chapter 6 explores the application of the CARTI across rural local authorities in England. Three case studies were undertaken based on the CARTI results. Further discussions with transport professionals were carried out in order to review the effectiveness of the index. An evaluation is performed of the CARTI as a national planning tool to assist the effective implementation of CAEVs in rural areas.

Chapter 7 completes the thesis with a conclusion, which collates the findings from each thesis chapter, and the success of the research in relation to the original research aim and objectives is evaluated. Finally, Chapter 7 describes recommendations and suggested further work based on the thesis findings.

Appendices A to D provide supporting material for the research and are individually referenced throughout the thesis, including details of four conference and journal papers that have been published as a result of this research.

Table 0.1 Relationships between thesis objectives, chapters and methodologies

		Objective				
		A	B	C	D	E
Chapter	1	Literature review	Literature review		Literature review	
	2	Literature review	Literature review	Literature review		
	3			Practical experiments		
	4	Interview discussions		Survey and Interviews	Survey and Interviews	
	5		Review of transport indicators		Development of CARTI	Development of CARTI
	6		CARTI Case Studies		Review of CARTI	Review of CARTI
	7					Evaluation of thesis

Table 0.1 concludes the introduction to this thesis by visually representing how the methods within each thesis chapter contribute to the exploration of this thesis's objectives and therefore contributions to knowledge. Having introduced the themes of this research, the following chapter contains an extended literature review of the current state of rural-based transportation and explores the requirements needed for improvement. It is in Chapter 1 that the need for this thesis as a contributive piece of research work is established.

1 RURAL TRANSPORT SYSTEMS

Whilst congestion, traffic accidents and mobility gaps remain major transport challenges, the sustainability and decarbonisation of transport have become additional central issues (Rodrigue, 2020b). For transport to be sustainable, mobility solutions must be accessible, equitable, efficient, safe, and climate responsive (Sustainable Mobility for All, 2017). Integrated private, public and active zero-carbon transport systems are needed to meet the environmental, social and economic needs of rural communities (Sustainable Mobility for All, 2017, Whitelegg et al., 2010).

The following concepts explored in this chapter are referred to throughout this thesis, and the investigations into the literature aim to contribute to the understanding and promotion of these concepts in relation to rural transport planning and CAEV implementation. This chapter explores the meaning of these concepts and reviews the current state of these concepts in UK and rural contexts.

1.1 Rural Definition

The distinction between the terms *urban* and *rural* is important for this thesis. In the UK, an urban area is classified as containing a settlement of over 10,000 people. A rural area is classified as containing a settlement of less than 10,000 people. These are the standard definitions used in the Rural Urban Classification (RUC) 2011 (Bibby and Brindley, 2013b). 82% of the UK's population live in urban areas, however, 85% of UK land area is classified as rural (Bibby and Brindley, 2013a). The urban-rural distinction is important when assessing the future role of CAEVs in the UK and around the world because, unlike humans, CAEVs cannot automatically distinguish their surroundings without sophisticated software.

The RUC distinguishes urban and rural environments purely by population. It does not consider wider economic, social, or cultural distinctions across areas (Bibby and Brindley, 2014). For this study, it is important to note that the RUC takes no specific account of land cover, roads, or the physical natural environment, although to some extent there is often a correlation between population classification and the natural environment in which those populations sit. Therefore, the RUC cannot be solely relied on, especially as it has no relation to road types. To address this classification issue, a range of classification methods including the RUC, official UK road classifications, and visual photographs and satellite imaging have been integrated to define sub-rural and sub-urban categories. Various field studies were undertaken to determine how rural and urban road environments vary. A series of environment descriptions have been developed, accompanied by photographic examples, to summarise the range of environments a CAEV might encounter with respect to how CAEV positioning technology works.

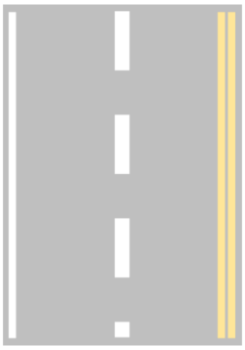
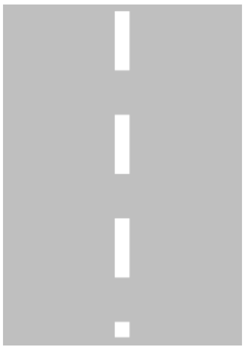
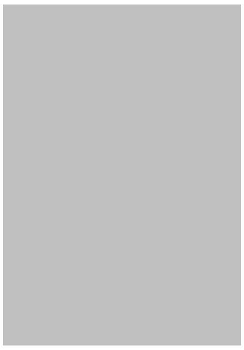
Using this method, the following definitions for urban and rural roads are applied throughout this thesis and are based on RUC 2011, road types and road marking densities (Table 1.1):

- Rural roads include all roads within RUC 2011 defined rural areas excluding motorways and medium and densely marked A-roads; however, including A-roads with light density or no road markings.

- Urban roads include all roads within RUC 2011 defined urban areas with the addition of all RUC 2011 rural motorways, including all rural A-roads with heavy and medium density road markings.

These definitions, adapted from RUC sub-divisions, are primarily based on road type and quality. Based on the photographic evidence collected during the road trials conducted and described in Chapter 3, the definitions above were found to be applicable, although this validation was based on subjective observations.

Table 1.1 Road mark density definitions

Category	Heavy	Medium	Light	None
Description	Describes multiple road features and includes extra driving information (e.g., location or speed).	Describes multiple road features - typically lanes AND road boundaries.	Describes a single road feature - typically lanes OR road boundaries.	No road markings.
Diagram				
Example				

1.2 Accessible Transport

Historically, rural areas have suffered with problems of inaccessibility (Midlands Connect, 2020a). High levels of poverty, social exclusion and inequality compared with urban communities can be directly linked to physical isolation and a lack of accessibility due to scattered and peripheral rural characteristics (Abreu et al., 2019, Bosworth et al., 2020, Lucas et al., 2016, Roberts et al., 2006, Velaga et al., 2012, Vitale Brovarone and Cotella, 2020). Improving accessibility is therefore fundamental to the development of transport solutions and the rural socioeconomic systems they serve (Cheng et al., 2007, Vitale Brovarone and Cotella, 2020). Universal access requires transport systems to be inclusive and a continued lack of access to services and technology keeps rural communities isolated from their urban counterparts (Abreu et al., 2019).

There are multiple aspects to rural accessibility rather than purely the provision of physical and reliable transport services. Universal access must be equitable and inclusive physically, financially and digitally, so that no one, irrespective of personal or geographical circumstance is left behind (Sustainable Mobility for All, 2019). The challenge of providing access and connectivity to rural communities is made worse by the combination of poor physical transport services as well as digital exclusion, where digital technologies can contribute to more effective public transport services (Sustainable Mobility for All, 2017, Velaga et al., 2012).

In the Midlands, 76% of rural journeys are made by private car or van, compared with 53% in urban areas and weekly transport costs are on average £58 higher (Midlands Connect, 2020a). This highlights a lack of affordability, a form of accessibility, where generally poorer rural residents are forced to pay high transport costs, mostly to purchase and maintain their own private vehicles to access education, employment and essential services. The natural characteristics of rural areas result in unavoidable distance challenges, and it cannot be expected that rural travel time will ever meet those of urban areas. For example, secondary school students in the rural Midlands travel an average of seven miles to school compared with 2.8 miles in urban conurbations (Midlands Connect, 2020a). However, access to convenient and affordable transport to enable rural dwellers to get to services is a priority.

1.3 Traffic Safety and Health

A safe transport system avoids fatalities, injuries and crashes be they accidental or intentional. When mobility solutions are unsafe, they pose significant health risks which can result in social and economic losses. For example, 97% of transport deaths worldwide are road transport related and account for 93% of costs (Sustainable Mobility for All, 2017). In the UK, data from the Department for Transport (DfT) indicates that on average 59% of traffic fatalities occur on rural roads annually (Figure 1.1, Figure 1.2), despite rural roads accounting for less than 50% of road traffic kilometres travelled (DfT, 2021e, DfT, 2019b, DfT, 2015). In fact, traffic fatalities are distributed across rural roads, urban roads, and motorways in similar proportions to total road length in kilometres, rather than proportion of traffic kilometres travelled by the UK population as shown in Figure 1.2.

Table 1.2 Factors contributing to fatal traffic accidents in the USA (extracted from Fagnant and Kockelman, 2014: page 5)

Human or Environmental Factor	Contributing Factor	Percentage of Fatal Accidents (%)
Human	Alcohol use	31
Human	Speeding	30
Human	Distracted driver	21
Human	Prohibited driver errors	21
Human	Failure to keep in lane	14
Human	Failure to yield right-of-way	11
Environmental	Wet road surface	11
Human	Erratic vehicle operation	9
Human	Inexperience	8
Human	Drug use	7
Environmental	Ice, snow or debris	4
Human	Fatigue	3

These disproportionately high numbers of rural road fatalities are in-part a result of the irregular, winding and narrow nature of rural roads, in contrast to the typically uniform and predictable nature of urban roads and motorways (ROSPA, 2017). In addition, human error is the causal factor for over 90% of traffic accidents (Fagnant and Kockelman, 2015, Jones et al., 2018, TSC, 2017). A breakdown of fatal crashes and their causes in the USA can be found in Table 1.2 (Fagnant and Kockelman, 2014).

Both Figure 1.1 and Figure 1.3 highlight the impact of COVID-19 on traffic in the UK in 2020 (*) with fatalities dropping suddenly from 2019 levels. Due to this anomalous data, Figure 1.2 uses 2019 data to better demonstrate the current expected transport statistics post-COVID-19.

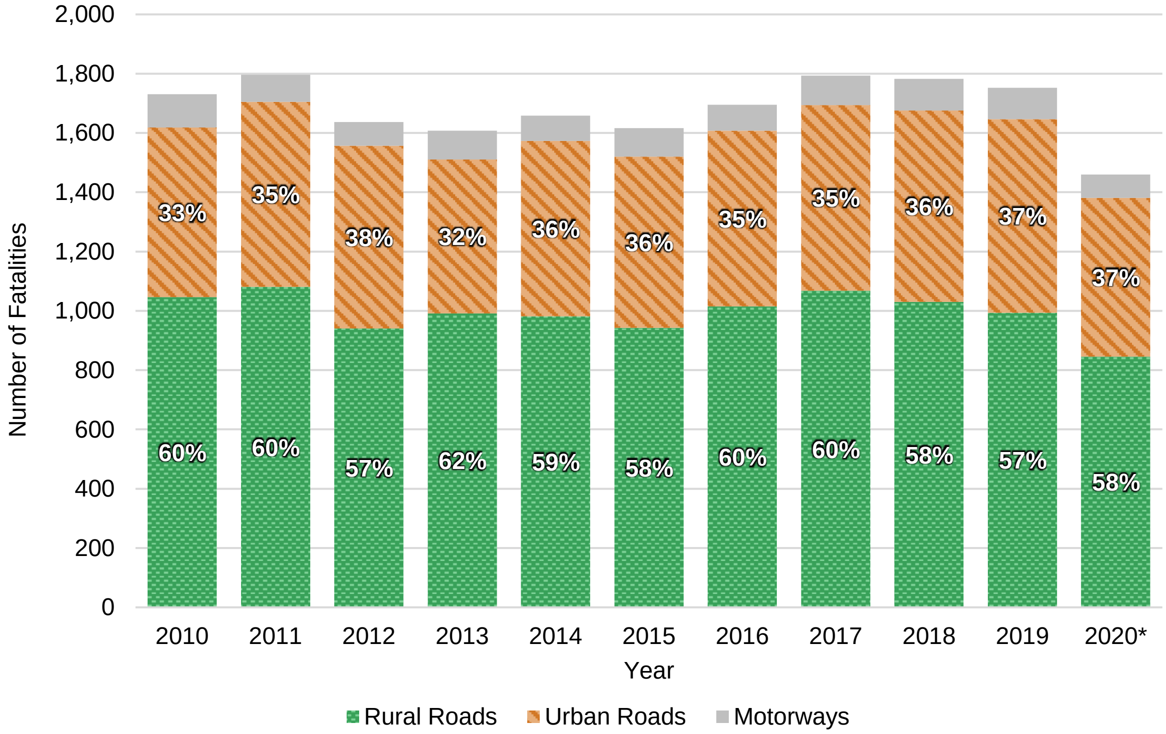


Figure 1.1 UK road fatalities by road type 2010 – 2020 (extracted from DfT, 2021e: interactive dashboard page 2)

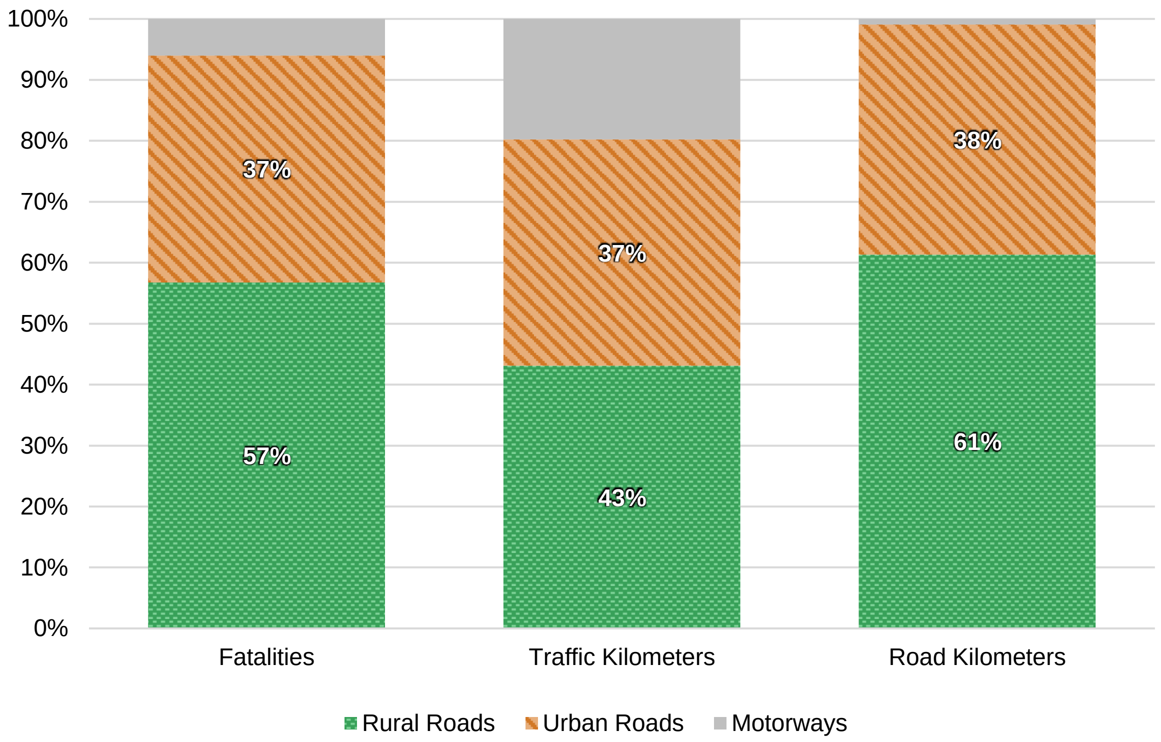


Figure 1.2 Proportions of UK traffic fatalities, traffic kilometres, and road kilometres by road type 2019 (extracted from DfT 2021e: interactive dashboard page 2)

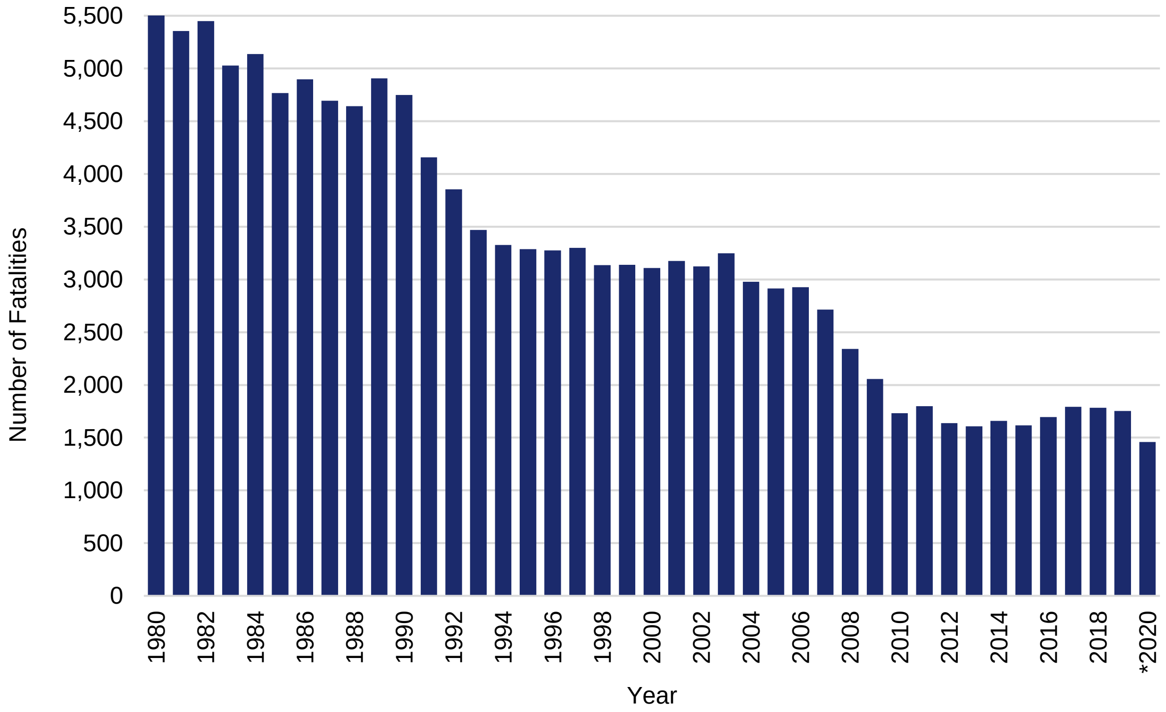


Figure 1.3 Total UK traffic fatalities 1980 – 2020 (extracted from DfT, 2015, 2021e: interactive dashboard page 2)

Previously, technological improvements in vehicles and highway engineering; more effective road safety policies and enforcement; and improvements in education and training, all of which have brought about behavioural change, have led to the dramatic reduction in road fatalities since the 1980s (Figure 1.3). Even since 2006, UK road fatalities have almost halved (DfT, 2021g). However, over the past 10 years, total UK road fatality numbers have remained constant and within roughly the same proportions across rural and urban roads and motorways, with rural roads remaining the contributive majority (Figure 1.1). This plateau of fatalities across ten years suggests another transformative step in transport is needed to further reduce traffic fatality figures.

Since their inception, private cars have continued to provided people with unprecedented levels of mobility and accessibility, and are a necessity for many rural dwellers to enable them to access essential services (Midlands Connect, 2020a). However, high levels of private car use, as demonstrated in rural areas (Vitale Brovarone and Cotella, 2020), has resulted in increased emissions and air pollution (Cheng et al., 2007). Although the health of urban dwellers is typically the primary concern when considering local air pollution and health, with increasing implementation of alternative urban transport and congestion charging rural areas are at risk of being left behind as car ownership increases. In addition, typically fast and poorer quality rural roads contribute to noise pollution in rural areas.

1.4 Digital Connectivity

The additional challenge of digital connectivity is increasingly prominent particularly with regard to rural transport accessibility. Now in the period of the "fourth industrial revolution" development solutions fuse together technologies and blur the lines between the physical, digital and biological (Schwab, 2017). As a result of this technological convergence, digital technology will form the backbone of mobility in the future (Sustainable Mobility for All, 2017). Telecommunications themselves, in well-connected areas, are now a realistic substitute for travel. However, when physical travel is required, new transport technologies will likely depend on high-speed, reliable internet connectivity and upon people having the skills and confidence to use it. Presently, poor transport infrastructure is consistent with under-developed telecommunications infrastructure (Philip et al., 2017, Salemink et al., 2017, Velaga et al., 2012) and, compared to other sectors, the transport sector is less ready to embrace digitalisation (Sustainable Mobility for All, 2017). This is a concern when in the last couple of years the adoption of digital working methods due to COVID-19 has advanced the rate of digital communication development by up to ten years (WTO, 2020). Therefore, there is now a more urgent need to bridge digital divides between urban and rural communities and the transport sector.

The potential gains from integrated transport and rural digitalisation are huge, providing unrestricted access to online commerce and markets (Sustainable Mobility for All, 2017). Further digital and technological advances support innovation, extend connectivity and enhance wellbeing (Bosworth et al., 2020). Transport solutions integrating digital communications, such as Mobility as a Service (MaaS), reduce the need for widespread private vehicle ownership and improves social inclusion, access and reduces isolation. Rural MaaS should integrate different forms of transport and interchanges with suitable digital infrastructure to achieve these benefits (Hensher and Mulley, 2020). With digital connectivity and technologies, vehicles have the potential to be shared between users with real-time tracking, demand prediction and digital scanning. This will reduce handover costs and electronic payments will reduce transaction costs and time (Bosworth et al., 2020).

Despite this potential, rural communities are particularly vulnerable to digital exclusion and can often not benefit from the technologies which streamline transport services such as MaaS and transport sharing (Sustainable Mobility for All, 2017). This is a result of multiple factors. Economically, disassociated transport budgets mean that transport resources, such as minibuses, for one group are unused whilst other groups cannot access transport. Further, uneven communications infrastructure distribution results in inequalities in digital skills and uptake among local rural populations, whilst at the same time being unattractive to digitally skilled people and businesses. Socially, transport sharing is scarce due to ingrained personal and private mobility habits, whilst older generations are often not adept at using digital technologies whilst also being physically isolated (Bosworth et al., 2020). This widens digital exclusion. As an example, advances in online healthcare do not necessarily translate to accessible healthcare depending on individual circumstance.

Improving digital connectivity, promoting and developing rural skills, attracting entrepreneurs and investment with rural socio-cultural factors, and effective and available networking and meeting spaces are all factors that can contribute to rural economic growth. However, aging communities and associated health, isolation and social wellbeing factors, are increasingly prominent across literature. These contribute to limiting rural economies and exacerbating hidden poverty, inequality, and social exclusion (Bosworth et al., 2020). Typically, rural areas are presented as having few resources and institutions, low economic diversity and poor access to markets unlike cities. However, increasingly digital accessibility and cohesive communities (a common rural characteristic) offer alternative foundations for sustainable rural growth. To deliver opportunities to develop rural distinctiveness and address local needs internal and external digital and physical connectivity is essential (Bosworth et al., 2020). At present, personal rural transport costs are high and poor transport services and accessibility continue to create barriers to rural development (Midlands Connect, 2020a, Sustainable Mobility for All, 2017). Alternative rural transport solutions are needed to remove these barriers and actively contribute to connecting and integrating rural communities and their economic opportunities. This would encourage rural-based investment from industry and government.

Although strong digital connectivity is key to strengthening rural economies, and is critical to future transport systems (Bosworth et al., 2020, Sustainable Mobility for All, 2017), physical mobility still remains fundamental to a smart countryside for functional and social needs. Recognising the social value of mobility can sustain personal wellbeing so the social function of mobility must be built into any future rural strategy (Bosworth et al., 2020, Slee, 2019). Those representing rural areas need to understand and promote rural needs and opportunities before the diffusion of new mobility technologies become urban-centric and challenges the UK DfT Future of Mobility Strategy (DfT, 2019a). This strategy incorrectly assumes that new mobility technologies tested and implemented in urban cities could be transferred to rural areas.

> *"Using our towns and cities as testbeds for innovation, we will trial and improve upon products and services that can be adapted across the country and across the world."*

Department for Transport, 2019: page 15

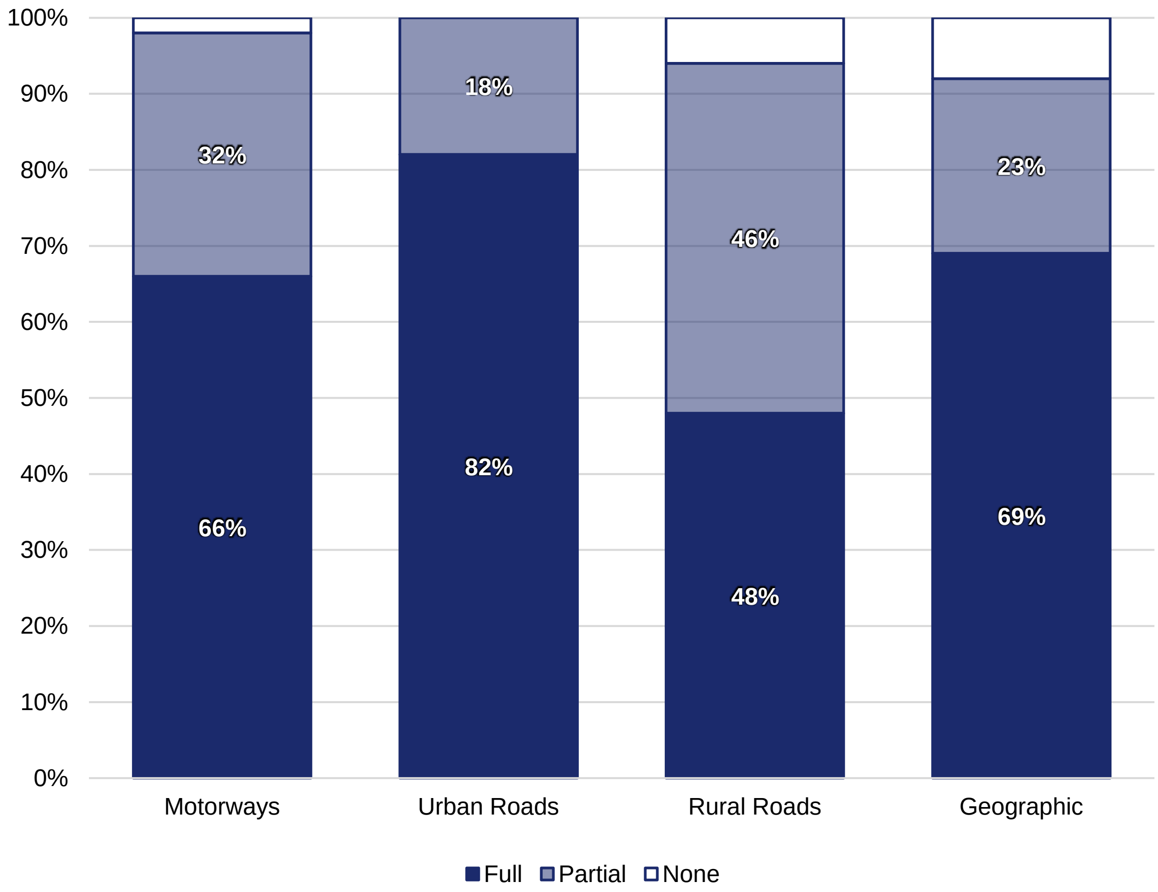


Figure 1.4 UK 4G mobile internet coverage (extracted from Ofcom, 2021: page 43)

4th Generation (4G) mobile coverage is essential to meet demand for online and connected services. If transport solutions are to integrate and rely on communications infrastructure, 4G coverage is currently the fastest, most reliable, and most universal and wide-spread method with which to do so. However, digital infrastructure in the UK, including 4G, presently best serves urban communities and is not equitable across rural communities, although this is improving (Gowling WLG, 2018). In 2017, only 18% of UK roads had full 4G coverage (Scharring et al., 2017), but in 2021 48% of rural roads had full 4G coverage as shown in Figure 1.4. In Figure 1.4, full coverage refers to each of the four UK mobile network providers (EE, O2, Three, Vodaphone) all providing reliable 4G coverage in the same location. Partial network coverage means that at least one, but not all, of the four UK network providers provides reliable signal (Ofcom, 2021).

Despite improvements in recent years, poor coverage across UK means that some vehicle manufactures have said that the UK market is not a viable one for launching new transport technologies (Scharring et al., 2017). This gives the UK an economic incentive to develop digital connectivity across UK roads.

Whilst the ongoing rollout of 5G coverage in major UK cities, and on some major roads, will help to achieve even greater quality connectivity than 4G (DCMS, 2017), this will again leave the already digitally isolated rural communities further cut off from the most advanced connectivity. Due to the short range and infrastructurally intense nature of 5G communications, it is presently unlikely rural areas and communities will ever realistically see 5G connectivity (Seymour et al., 2017). Fully connecting rural UK areas is perhaps more important than improving the connectivity speeds of those who already have it.

1.5 Sustainable Transport Systems

The concept of sustainability remains open to interpretation and often requires context-specific understanding (Purvis et al., 2019). The highly referenced Brundtland Report (World Commission on Environment and Development, 1987) provides the most prolific definition of sustainability as:

> *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

World Commission on Environment and Development, 1987: page 16

In addition to this baseline definition, the three-pillar model of sustainability, which is now ubiquitous, emerged gradually as academic literature united the concepts of society, economics and ecology and referred to each as vital interacting systems, or interrelated perspectives, for consideration in the field of sustainable development (Purvis et al., 2019). In practice, the three-pillar model demands a balanced approach to sustainable development where social, economic, and environmental issues are considered equally. Development solutions, therefore, should not favour one pillar over, or to the detriment of, either of the other two.

Although sustainability is relatively well defined, there is no single universally accepted definition of "sustainable transport" (Castillo and Pitfield, 2010, Jeon and Amekudzi, 2005). As the term suggests, the three pillars of sustainability must play a substantial role in any transport system defined as sustainable with one study identifying that many of the definitions of sustainable transport capture aspects of system efficiency, social quality of life, economic impact, and environmental impact (Jeon and Amekudzi, 2005, Jeon et al., 2013). Further, other studies look to identify themes common across sustainable transport development literature. For example, liveable streets and neighbourhoods; protection of the environment; equity and social inclusion; health and safety; and support of a vibrant & efficient economy are defined as the five elements of a sustainable transport system (May et al., 2001). These were found to be supported by the majority of similar literature (Castillo and Pitfield, 2010). A later study looks at a range of transportation planning sustainability concepts including eco-centric, anthropocentric and holistic sustainability which all include the three pillars, however, they also include liveability, health and resilience as important factors that sustainable transport systems should be promoting (Ramani, 2018).

Sustainable transport and mobility are fundamental to global progress in realising the 17 Sustainable Development Goals (SDG) (Sustainable Mobility for All, 2017) (United Nations, 2021). Although there is no single transport-centric SDG, three of the SDGs reference transportation (3.6, 9.1, 11.2) and transport is recognised as a critical contributor to achieving many of the other SDGs (Regmi and Gudmunsson, 2017, Roberts et al., 2006)(Sustainable Mobility for All, 2017). These analyses of transport and the SDGs highlight the need for sustainable transport systems which positively integrate multiple aspects of global development whilst fundamentally being safe and non-pollutive. This defines effective and sustainable transport.

1.6 Transport Emissions and Climate Change

The production of carbon dioxide (CO_2) and other greenhouse gases (GHG) is directly related to increasing global warming which is changing the earth's atmosphere, ocean, and biosphere. These changes result in more frequent and intense atmospheric and climatic events such as heatwaves, droughts, precipitation, storms and reductions in sea ice, snow and permafrost, the effects of which contribute to global sea level rise and flooding (IPCC, 2021a). To mitigate these changes, human-induced global warming must be reduced to at least net zero CO_2 emissions, along with strong reductions in other GHG emissions (IPCC, 2021b). Net zero refers to achieving a balance between the amount of GHG emissions, including CO_2, produced and removed from the atmosphere (Shepheard, 2020).

The UK has targets to reduce carbon emissions to net zero as part of its commitment to the 2016 Paris Agreement, the goal of which is to limit global warming to 1.5 degrees Celsius (°C) compared to pre-industrial levels (UNFCCC, 2021). In April 2021, the UK government committed to reducing carbon emissions by 78% by 2035 (Harrabin, 2021). In August 2021, the Intergovernmental Panel on Climate Change (IPCC) warned that urgent action to reduce emissions was needed, advising that cutting emissions to net zero by 2050 would likely limit global warming to 1.5°C in the long-term and help to avoid the worst effects of climate change (Trevelyan and Sharma, 2021).

These emerging climate challenges, with the addition of new working styles in the wake of COVID-19, highlight a need for sustainable rural communities developing around eliminating dependence on fossil-fuelled mobility (Bosworth et al., 2020). In the UK, transportation accounts for the largest proportion of CO_2 emissions of any sector and transport is the only sector for which emissions have increased since 2010 (Curd, 2020, Hawkes, 2021). This is also the case worldwide where specifically road transportation is the biggest contributor of CO_2 emissions, responsible for 75% of global GHG emissions. This is predicted to be the case until at least the year 2050 (Zawieska and Pieriegud, 2018).

Reducing these emissions is critical for the sustainable development of the transport sector. Since their inception, private cars have continued to provide people with unprecedented levels of mobility and accessibility. However, increased car ownership has had negative impacts on the environment that need to now be mitigated (Cheng et al., 2007), particularly in rural communities that are highly car-dependent (Vitale Brovarone and Cotella, 2020). The development and implementation of alternative fuelled vehicles such as battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV), which produce zero emissions on the road, are already contributing to change. However, for sustainable transport systems to be truly realised there is a need, not just environmentally, but socially and economically as well, for transport systems which seamlessly integrate motorised, public transport and active modes to serve society (Sustainable Mobility for All, 2017). These integrated, zero-carbon transport systems are fundamental for the development of socioeconomic principles including improved quality of life, reduced social exclusion and improved accessibility to public services and opportunities (Whitelegg et al., 2010).

Whilst the pillars of sustainability promote the equal enhancement of societal, economic and environmental aspects, it is common for solutions to simply reduce, limit or completely remove potential negative environmental impacts. As such, environmental enhancement is rarely considered, particularly when implementing transport solutions. Therefore, there is a case for transport development solutions to positively, rather than neutrally, impact the environment as it strives to do socially and economically.

1.7 Concluding the State of Rural Transport Systems

This chapter explored the current state of rural road-based transport systems addressing challenges of accessibility, safety, digital connectivity, sustainability, and pollution. Rural communities continue to lack physical and financial accessibility compared with urban counterparts and are left with expensive and inadequate solutions. In terms of safety, there has been no significant reduction in total rural traffic fatalities for ten years; suggesting a fundamental change in the transport system is needed. Further, an already wide digital connectivity gap risks getting wider as new digital systems, mostly developed in urban areas, continue to integrate with and control developing transport systems. Ultimately, transport systems need to be sustainable within the contexts that they are implemented, considering the local and global environment, societal needs, and economic systems. In rural areas, it is particularly challenging to balance these pillars of sustainability.

Throughout this chapter, an urban-rural divide has been identified with rural communities facing greater accessibility issues, road traffic safety concerns, economic challenges relating to isolation, and digital exclusion. Referencing the SDGs, sustainability is built on equality and a balance between social, economic and environmental domains. However, there is a clear imbalance between urban and rural areas in relation to transport systems and solutions. In the interests of sustainability, a theme that runs throughout this thesis, there is a need for this research to highlight and address some of the specific transport challenges facing rural communities and promote the development of sustainable and technologically enhanced transport solutions which will have positive, rural-specific impacts. As the following chapter suggests, CAEVs are such a solution.

2 CONNECTED AUTONOMOUS AND ELECTRIC VEHICLES

Intelligent Transport Systems (ITS), increasingly referred to as Intelligent Transport Systems and Services (ITSS), aim to solve transport demand and emissions challenges and make transport solutions safer, more efficient, and therefore more sustainable(Anonymous, 2017d). In an increasingly congested and technologically advancing world, large and expensive transport infrastructure solutions are no longer viable, particularly in cities (Armitage, 2019, Wyllie, 2019). ITSS offers an effective alternative and can be achieved through the integration of existing and developing technologies. Current focus is on the development of Connected, Autonomous and Electric Vehicles (CAEV) to meet the current challenges in transport. Therefore, CAEVs are currently among the most researched automotive technologies (Vdovic et al., 2019). The ITS Handbook defines ITS as a generic term for the integrated application of communications, control and information processing technologies to the transportation system (Miles and Chen, 2000). ITSS are therefore data driven. Data is acquired from the transport system or infrastructure, the user, and from external databases. This data is then processed to provide information to the user to aid driving decisions. From this early success in merging ICT with transport infrastructure, other systems are now in place that control access to highways, impose variable speed limits, advise on lane discipline, and provide driver information about weather and traffic characteristics to reduce congestion, accidents and journey times (Stephenson, 2016). These advantages have associated individual to wider national economic benefits across transport networks.

CAEVs bring together a number of transport technologies to provide a solution capable of autonomous driving functions and wireless connectivity which are powered by an electric-based power source. The combination of these technologies is predicted to positively transform mobility services at reduced costs creating safer, more efficient and sustainable transport systems (Burns et al., 2013, European Commission, 2019a). Whilst CAEVs have broad applications across a variety of sectors including private and public transport, rail, aerial, marine, agriculture, and working in hazardous environments, this thesis focuses primarily on road-based public, private and shared motorised vehicles. One of the greatest advantages of CAEVs is their ability to increase the safety and fluency of traffic, resulting in uninterrupted journeys (Dokic et al., 2015). CAEV technologies will therefore increase consumer's free-time, improve mobility, and reduce emissions, land use, and insurance costs (Meyer, 2018).

For CAEVs to be successfully and effectively implemented they need to be sustainable; not compromising the health of the environment, having societal benefits, and bringing long-term economic growth to the communities they serve. They also need to be safe, efficient and accessible. Widley cited initial barriers to the implementation of CAEVs include the effectiveness of the technology, high technological costs, experimental and untested technology, user perceptions and trust, and regulatory challenges (Bagloee et al., 2016, CCAV, 2017, Cui et al., 2017, Fagnant, 2014, Filip et al., 2017, Kalra, 2017, Murphy et al., 2017, Wood et al., 2012).

CAEVs are a technology that have the potential to address rural social and economic needs and help close the gap between rural and urban communities (Bosworth et al., 2020). It is important that the potential benefits of CAEVs will not only be experienced by those living in urban areas, especially as it is rural communities that are isolated, lack accessibility, who are at most risk of severe traffic accidents, and lack digital connectivity. Rural communities have a significant amount to gain from CAEV development and hence rural priorities and considerations should be central to future CAEV developments.

2.1 A Brief History of CAEVs

The concept of autonomous vehicles has existed for decades (Bagloee et al., 2016), but huge costs and technological infancy have hindered development and large-scale production (Fagnant and Kockelman, 2015). General Motors were one of the first companies to attempt road-vehicle autonomy with their automated vehicle highway system concept at the 1939 World's Fair (Bishop, 2005). Typically, early attempts tried to adapt both highway infrastructure as well as the vehicle including the Automated Highway Systems (AHS) developed by the California State Department of Transport in the 1980s (Miles and Chen, 2000). Since then, the development of connected in-vehicle infotainment systems and services have had an influence on the development of connected and autonomous vehicle functions, such as safety systems. Research and development into advanced vehicle connectivity and autonomy has steadily progressed from mitigation to the elimination of the negative effects of road transportation, such as pollution and accidents. In the case of accidents, personal passenger vehicle mitigation included the use of technologies such as seatbelts, airbags, crumple zones, and anti-lock brakes (ABS). More recently, many vehicle manufacturers have offered vehicles equipped with advanced driver-assistance systems (ADAS), such as adaptive cruise control and lane assistance, typically enabled through autonomous technologies, to eliminate accidents altogether. These initial autonomous technologies are now developing into more advanced and integrated CAEV solutions capable of fully operating a vehicle without driver assistance.

AV development took significant steps forward with the Defense Advanced Research Projects Agency (DARPA) Grand Challenge in 2004 (Stephenson, 2016). The challenge aimed to demonstrate the technical feasibility of autonomous ground vehicles over a 142-mile course and accelerate the development of the technical foundations for AVs. In the first year, the most successful team managed to cover 7.5 miles, but the course was successfully completed in subsequent competitions (DARPA, 2014). Following this, it was large technology companies including Google and Apple, that took the initiative to develop CAEV technologies for mass use, rather than the traditional automotive manufacturers (Kuchinskas, 2012). Tesla (founded in 2003) now leads the way in private CAEV development and mass-production. However, in 2011, China became the world's largest vehicle manufacturer, overtaking Europe and North America (Malek, 2012). In 2020, China’s EV market was the biggest in the world and emergent Chinese vehicle manufactures such as Geely, Nio and Xpeng continue to challenge Tesla in the CAEV market by producing efficient, long-range electric vehicles with autonomous and connectivity functionalities (Doll, 2021, Zhang and Zhu, 2021).

Today, most major vehicle manufacturers are developing some form of autonomous vehicle. Legislators are also working towards providing suitable legal and operational environments for AVs. National and local governments around the world have generally moved towards enabling vehicle autonomy, with the United Nations (UN) amending Article 8 of the Convention on Road Traffic in 2014 to allow autonomous vehicles to operate on roads (Gesley, 2016). Since then, the UN has published a framework specific to the safe implementation of autonomous vehicles (ECE, 2019).

The need for effective CAEV policy and operational environments due to the rapid and continuing development of CAEVs prompted the UK government to create the Centre for Connected and Autonomous Vehicles (CCAV) in 2015 (CCAV, 2020). The CCAV is a joint organisation between both the UK Government's Department for Transport (DfT) and Department for Business, Energy and Industrial Strategy (BEIS) dedicated to the safe and reliable development and implementation of CAEVs and their technologies. The CCAV aims to maintain the UK's high standard of CAEV development; provides guidance and funding to early CAEV projects; and prepares the UK for regulatory change. The CCAV helps to maximise the economic and social benefits of new CAEV technologies whilst ensuring that only safe, secure, and efficient technologies are developed (CCAV, 2017, CCAV, 2019). Since 2015, the UK government and the CCAV have invested £378 million into CAEV research and development, trials, testbeds, simulation and modelling, and pilot services. The CCAV are currently undertaking a three year review of the regulatory framework for the safe deployment of CAEVs within the UK (CCAV, 2020).

2.2 Autonomous Vehicles

Often referred to as "driverless" or "autopilot", AVs feature autonomous system technologies that allow them to perform driving functions without human input. The SAE's levels of vehicle autonomy refer directly to AVs. For a vehicle to operate autonomously to a level of safety equal to or beyond that of human driving, connectivity and information provision are important. Therefore, whilst a CV can exist without AV functions, an AV, particularly when it comes to the higher levels of automation, will most likely require some sort of connectivity offered by CVs. As the technologies on both sides develop and become integrated with vehicles, it can be expected, and in fact can already be seen, that CAVs will emerge as one integrated connected and autonomous solution (Penta Security, 2018)

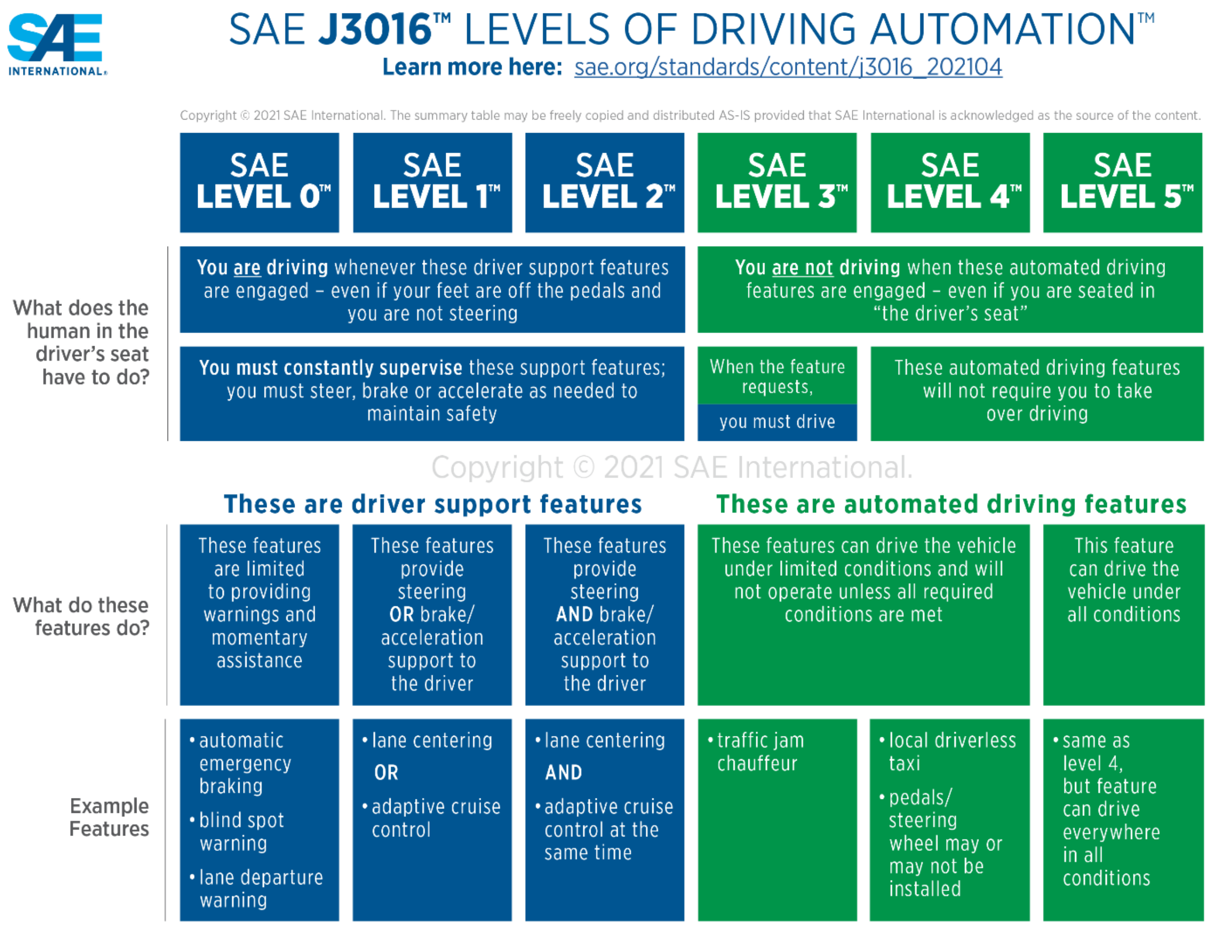


Figure 2.1 SAE Automation Levels (SAE, 2021: J3016_202104)

There are varying levels of autonomy for CAEVs defined by SAE International (SAE, 2021). Figure 2.1 defines these levels and, whilst primarily concerning road vehicles, the basis of each level can be applied across all potential CAEV sectors. Each level details autonomous functions of a vehicle and defines the level of human interaction, if any, required to operate the vehicle (Shuttleworth, 2019).

When discussing CAEVs throughout this thesis, the author is typically referring to CAEVs with automation levels 3 or 4 unless otherwise specified. At level 3, the vehicle is automated but requires human supervision, with the ability to request human takeover of the vehicle where necessary. At level 4, human takeover is not required, although human supervision is. As opposed to level 5 CAEVs, which can operate autonomously in all conditions, level 4 will only operate if specific conditions are met. Whilst level 5 CAEVs have been considered, this technology, specifically in rural scenarios, is underdeveloped and unlikely to be achieved in the near future to which this thesis refers.

Real-time vehicle positioning (regarding location and sensing), dynamic connectivity, and dynamic mapping are the three key technologies required for the successful development of CAEV transport. On top of the sustainability requirements for CAEV development, the technology must be reliable, accurate, and continuously available (Stephenson et al., 2013b). Effective real-time positioning is required for CAEV autonomy and can be achieved through a combination of on-board positioning, satellite, and mapping techniques.

On-board positioning enables a CAEV to effectively 'see' its surroundings. The primary purpose is to prevent collisions and to help the CAEV to understand the changing environment around it. CAEVs use a combination of sensor technologies that include range detection sensors, such as: radar and LiDAR (Light Detection and Ranging), that determine where other objects are in relation to the vehicle; and visual sensors, such as cameras, which can detect finer details and colour. Cameras, with the help of software, can categorise detected objects and can also read road signs and markings, allowing the CAEV to make the necessary adjustments to its position. These range sensors and cameras continuously monitor the local environment 360 degrees around the vehicle (Milford and Roberts, 2017).

Satellite positioning meanwhile is required to determine a CAEV's global position and location on roads by using the Global Navigation Satellite System (GNSS), which combines the systems of the United States (GPS), Russia (GLONASS), China (BDU) and others to provide continuous and accurate global positioning capability. GNSS receivers receive communication signals from GNSS satellites. The receiver requires four satellites to be electronically visible at any given time and uses the signals to calculate the distance from each satellite. The receiver can then determine its position and, if moving, its velocity (Hofmann-Wellenhof et al., 2008). A GNSS receiver is an effective tool for tracking, positioning, and navigation when mounted onto a CAEV (Wright et al., 2003). Utilising real-time kinematic (RTK) GNSS positioning can provide CAEVs with frequent, real-time positioning accuracies of less than 5 centimetres, but this relies on a static reference receiver. The shorter the distance between CAEV and static receiver, the greater the positioning accuracy (Stephenson et al., 2014). In countries such as the UK, networks of RTK (NRTK) static receivers can cover entire regions, which improves positioning flexibility, helps to minimise errors, and allows CAVs to travel greater distances (Aponte et al., 2014).

However, over long distances there can be significant environmental changes which influence positioning capability. For example, significant atmospheric changes can distort signals and reduce positioning accuracy. There are, however, mathematical computer models developed to combat these distortions (Hofmann-Wellenhof et al., 2008). Another significant challenge comes when receivers lose lock on GNSS satellite signals due to physical obstructions that interrupt the satellites' line of sight to the receiver, such as tall buildings, dense trees, and bridges (Stephenson et al., 2013a). These interruptions can cause cycle slips and a period of readjustment is needed until the previous accuracy is reacquired. For NRTK, the strength of the communication signal between the moving CAEV receiver and the stationary reference receiver can fluctuate. The receivers communicate via the UK's well-established mobile internet network which, although extensive, still has some poorly connected areas. Consistent coverage is a requirement for CAEV positioning. Data loss and message delay are therefore significant issues (Stephenson et al., 2014).

2.3 Connected Vehicles

Enabling road vehicles to wirelessly communicate between themselves, known as vehicle-to-vehicle (V2V) communications, the local infrastructure (vehicle-to-infrastructure – V2I), and the wider connected environment of the internet-of-things (IOT) (vehicle-to-everything – V2X), is delivering major safety benefits to transport systems (Neale et al., 2005). Strong and reliable V2X communications are vital to the continued improvements in ADAS and are essential for any CAEV ecosystem (Frenzel, 2017, Spirent, 2018). However, whilst CVs with V2X capabilities are integral to integrated and optimised CAEV and ITS services (Penta Security, 2018), neither autonomous functionalities nor electrical operation are requirements of CVs (Vaidya and Mouftah, 2020).

Today's modern vehicles use 4G LTE (4th Generation Long Term Evolution) as the preferred communication mode, due to its relatively high data rates and smartphone compatibility (Malek, 2012) allowing it to receive traffic and vehicle information and updates over the internet from mobile network providers. In the UK, these providers are EE, O2, Three and Vodaphone. However, to enable true V2X functionalities, more direct and localised communication methods are needed. Presently, there are two competing communication types: Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X).

DSRC is a Wi-Fi variant defined by IEEE 802.11p standards. DSRC is allocated the 5.850-5.925 GHz frequency range and divided into 7 channels. DSRC can achieve data rates of 3 to 27 Mb/s up to 300m, so range is limited (Bettisworth et al., 2015, Qualcomm, 2018). DSRC was specifically designed to transmit basic safety messages (BSM) between moving vehicles including location, direction, speed and braking, which trigger safety warnings to the driver and automates actions such as emergency braking. BSMs can be updated and transmitted 10 times per second with latency of <25ms. Given that DSRC has been in development since 1999, it is now well established, available and proven to be reliable (Bettisworth et al., 2015, Frenzel, 2017). As an alternative, C-V2X was defined as an LTE Direct technology in 3GPP Release 14. C-V2X uses existing cellular 3GPP standards (3G, 4G, 5G) but provides additional options such as device-to-device (D2D) communications; enabling V2X. This direct approach avoids the use of cell sites and networks and therefore network congestion. C-V2X can also broadcast to multiple users at once (Frenzel, 2017). C-V2X is faster than DSRC with latencies of approximately 5ms, is well developed, and has greater development potential. However, equipment costs and service agreements are barriers, as well as the uncertain future path of cellular technologies. Despite this uncertainty, it is predicted that fast, low latency 5G is the future of this option, particularly in cities (Qualcomm, 2018).

Whilst well-established and designed specifically for V2X applications, DSRC suffers from congestion and has little room for development. In the absence of DSRC adoption, the C-V2X alternative has become equally popular as cellular technologies have rapidly developed. There has therefore been significant opportunity for C-V2X to be established as the primary communications medium for V2X applications. However, it is likely CAEV solutions will use a combination of C-V2X and DSRC communication technologies to enable a wider range of V2X applications.

Satellite positioning and on-board sensor technology primarily provide a CAEVs autonomous functions, whilst V2X technologies provide the connectivity required to enhance positioning capabilities. Enabling V2X moves towards a cooperative driving experience that collectively prevents accidents, where neighbouring road vehicles directly and wirelessly share position and velocity information, and data on road and traffic conditions either within or outside of line-of-sight (LOS), to enhance CAEV situational awareness. Further, V2X technology provides back-up safety functions, required if the primary positioning technologies become inaccurate, fail completely, or if the CAEV struggles to function in extreme weather conditions. They are also capable of providing enhanced personal safety, fuel efficiency and emission reduction as well as improving traffic management(Anonymous, 2017a).

Despite these advantages, CV technologies face challenges of network coverage and signal strength reliability, especially in rural areas(Anonymous, 2017a). Additional barriers to consistent V2X communications include integrating autonomous systems, complex wireless-environment requirements, susceptibility to interference and cyber-attacks, consistent regulation and standardisation, and rapidly changing market conditions (Spirent, 2018).

2.4 Electric Vehicles

In the last decade EVs have emerged as realistic sustainable transport alternatives to traditional internal combustion engine (ICE) vehicles (Vdovic et al., 2019). In contrast to ICEs, EVs are powered by electric motors and use batteries to store electricity rather than fuel tanks to store petrol or diesel (Vaidya and Mouftah, 2020). Compared to EVs, the mechanical work required by an ICE to move a vehicle results in long delays due to a combination of processing time, mechanical implementation, electronic prediction and adjustment, and communication of information between different systems, before finally transferring the resultant energy to the vehicle’s wheels (Stephenson, 2016). In contrast, the delivery of power to the wheels of an EV is almost instantaneous as maximum torque is available from standstill. This makes EVs more responsive with quicker acceleration. EVs are a more environmentally friendly alternative to ICE vehicles, as they produce zero emissions at the source, reducing local pollution levels on roads and in cities. EV efficiency is also complimentary to vehicle automation, with Tesla and Google favouring EVs as the platform for effective vehicle autonomy.

The number of global EVs doubled to two million in 2016 since surpassing one million only a year earlier in 2015. It is estimated that there will be up to 70 million EVs by 2025 (Naceur et al., 2016). Key to EV advancements is the automotive software developed to manage increasingly complex interconnected electronic control units within the vehicles (Vdovic et al., 2019). The rapid adoption of private and public EVs in the UK supports the findings that connected and autonomous vehicles will rely on electric battery power (Alkheir et al., 2018, Damaj et al., 2020). This is preferable to ICE-powered vehicles for seamless connected and autonomous integration with vehicle systems and software (Vdovic et al., 2019). Compared to ICEs, EVs benefit from lower operating costs, greater efficiencies and minimal environmental impact (Damaj et al., 2020).

However, the currently limited range of EVs and requirements for available and reliable EV charging infrastructure are barriers to adoption (Damaj et al., 2020, Gowling WLG, 2018), particularly in rural areas. Plug-in hybrid vehicles (PHEV) are an option which combine traditional ICE with small electric batteries. These typically ensure that the most frequent shorter journeys are powered by electric, with the occasional longer journey making use of the ICE. PHEVs are therefore practical solutions for rural areas although are not zero-emission. Alternative zero emission fuels can also be considered. Hydrogen, either from natural sources or electrolysis, can be used as vehicle fuel. An on-board fuel cell combines the stored hydrogen with oxygen from the air and produces electricity to power the vehicle, heat and water from the exhaust (Charters, 2016). Hydrogen fuel cells are more efficient than the ICE but are very expensive as they are not yet mass produced at the same scale (Logan et al., 2020, van der Bulk, 2009). Also, whilst the range of a hydrogen vehicle can be much greater than an EV, the refuelling infrastructure is sparse (H2Stations, 2022). Hydrogen is seen as a realistic zero-emission alternative for electric heavy goods vehicles (HGV), however, the lack of refuelling infrastructure and efficiency compared to EVs suggests this is not yet a viable option.

2.5 Accessibility

Replacing, or supplementing, traditional public transport with alternative options such as demand responsive transport (DRT) can improve rural accessibility in a sustainable way (Dianin et al., 2021, Lakatos et al., 2020, Vitale Brovarone and Cotella, 2020). DRT can make use of many of the features of CAEVs including connectivity required to request the vehicle via a connected device such as a smartphone, and autonomy to locate the user and calculate efficient route options, particularly in shared transport scenarios. Mobility as a Service (MaaS) looks to support DRT though single travel management platforms that digitally unify the transport service process (Hensher et al., 2020) and requires open data sharing and reliable wireless communication infrastructure (Enoch, 2018). The efficiency benefits that could be achieved through autonomous and connected DRT and MaaS also look to reduce congestion and journey times for users. Such congestion improvements can be achieved through wide-spread levels of adoption of highly-automated vehicles (Cox and Hart, 2016).

CAEVs are also able to provide transport services to those unable to drive (Vaidya and Mouftah, 2020) and those that cannot assess public transport including the elderly, children and disabled, who are also classed as vulnerable road users. Further, CAEVs are expected to reduce the cost of transport overall and improve the affordability of mobility (see Section 3.4.6).

The Sustainable Accessibility and Mobility Framework (SAM) is a tool used by planners and decision-makers to prioritise sustainable transport interventions (Powell et al., 2021). The first priority is to substitute trips by encouraging people not to travel and to use technological means, such as online doctors' appointments, for which rural digital connectivity is vital. The second priority is for travellers to switch modes to more sustainable forms of travel, including active transport or public transport. It is this second priority where CAEVs and DRT can play a significant role by providing sustainable, effective and convenient transport solutions. The third priority is to switch fuels, encouraging travellers to use vehicles that are zero-emission.

To assist with developing the SAM solutions of digital connectivity and sustainable, active and public transport provision, the introduction of rural hubs to serve isolated rural communities is suggested. The concept of a transport hub takes the form of an accessible building or location, from and to which rural communities have access to a range of digital, social and physical transport connectivity services. Urban centres are often too distant from rural communities to effectively serve their transport needs, yet rural communities are often too small to establish their own transport provision and innovations (Slee, 2019). Given this, hubs look to provide a structure to the transport networks through which rural people can move and access services. If strategically designed, hub networks can promote sustainable travel solutions to influence user decisions regarding transport (LDNPA, 2018). In terms of CAEV implementation, DRT and MaaS services will require origins from which to operate, charge and be maintained, particularly in rural areas where communities can be separated by large geographical distances. Multi-modal and technological integrative transport hubs would effectively connect and serve peripheral rural communities. Beyond acting as simple transport stops, transport hubs have the potential to support other forms of mobility including the provision of retail collection and delivery, access to health services, provision of co-working spaces, and spaces for businesses to take advantage of improved rural footfall (Bosworth et al., 2020, Midlands Connect, 2020a, RTPI, 2021a). In this broader sense, rural transport hubs would look to become homes to solutions that address many rural social and community needs relating to isolation and inaccessibility (Bosworth et al., 2020).

2.6 Traffic Safety and Health

To improve road safety CAEVs are designed to either completely eliminate human error (Kalra, 2017) or enhance driver performance with automated functions such as brake assist (Rahman et al., 2018). Complete vehicle automation is expected to significantly improve road safety, with connectivity used to enhance safety through information sharing (Alkheir et al., 2018, Damaj et al., 2020, Jones et al., 2018). Given Figure 1.3, an evolutionary change in transport is required to break down the decade-long plateau of traffic fatalities. With the high proportions of deaths due to human error (Table 1.2), CAEVs and ITSS have the potential to generate this change. However, the technology needs to be distributed appropriately to ensure wide-spread safety and efficiency benefits across the country, and not solely in urban centres.

Congestion can result in traffic safety and driver health issues and is one of transports most common and growing challenges. The efficiency of CAEVs is therefore vital to overcoming congestion. Whilst governments continue to invest in hard infrastructure to increase road capacity, even in the UK (IPA, 2016), it is becoming more apparent that building to solve congestion is no longer a viable or sustainable solution (Lucas et al., 2016). CAEVs promise to improve traffic fluency via sensors allowing for less space between vehicles and guidance systems with real-time awareness of congestion (Corwin et al., 2015). These technologies will alleviate the transport systems of the future from congestion (West and Howell, 2016). Further relieving congestion and improving transport system efficiency is the drive towards increased vehicle sharing and public transport use that is to come with CAEV implementation. This will reduce individual car ownership and increase road capacity, enhanced by fleet platooning and more predictable traffic flows (Vaidya and Mouftah, 2020).

2.7 Digital Connectivity

The SAM framework places digital connectivity as the highest priority when attempting to develop accessibility solutions (Powell et al., 2021). As discussed, it is rural communities that are most at risk of isolation from essential services. Based on the SAM hierarchy, the provision of solely physical transport solutions, CAEVs or otherwise, is not sustainable. Digital accessibility solutions are required.

Although not the top SAM priority, CAEVs have an important part to play in terms of physical and digital accessibility. Whilst the digital divide between rural and urban communities is itself a barrier to rural CAEV implementation, the need to implement sustainable transport solutions such as CAEVs may accelerate the improvements to connectivity in rural communities and on rural roads, cellular or otherwise. Therefore, the implementation of CAEVs in rural areas provides an opportunity for improved rural digital connectivity.

2.8 Sustainable CAEVs

As discussed in Section 1.5, balancing the social, economic and environmental pillars of sustainability is critical to developing any rural transport system. If implemented correctly, CAEVs have the potential to be a truly sustainable solution.

Successful CAEVs will bring societal benefits by improving the safety of passengers, pedestrians and other road users; improving accessibility and reducing isolation; saving lives; reducing journey times; and improving mobility. The result of these improvements is that users will ultimately save time and money

(Lengton et al., 2015), relieving associated travel anxieties and improving mobility, productivity and social inclusion (European Commission, 2016).

These social benefits are widely acknowledged amongst the literature, but public surveys have returned mixed opinions on the development of CAEVs (Murphy et al., 2017). These opinions are ultimately down to the level of trust society has in the technology. Whilst trust can be achieved through rigorous testing and certification of effectiveness, people can still be unwilling to trust technology with their lives (Filip et al., 2017). Safety can be achieved from two directions. Bottom-up safety relies on a CAEVs individual, relative environmental perception technology and decision making systems, whereas top-down safety concepts focus on infrastructure and management systems such as fenced lanes and central controllers (Meyer, 2018). Ideally, CAEV development will incorporate both approaches to ensure that safety is a widespread and thorough aspect of CAEVs.

Economically, CAEVs have the potential to support local communities through transport cost savings from improved ease of travel, reduced accident costs, improved productivity, and increased trade. Once successfully implemented the provision of CAEV DRT and MaaS services will have substantial economic benefits (Alkheir et al., 2018, Enoch, 2018, Lakatos et al., 2020). There is also potential for job-creation including the maintenance, monitoring and operation of individual vehicles or fleets (Murphy et al., 2017), although it is unclear whether CAEV development will, overall, lead to job creation or loss. Cost-benefit analyses of CAEV implementation are ongoing, although one UK study suggests 320,000 new jobs could be created, and with them training and development opportunities (SAC, 2016).

Whilst for the individual user, overall average trip costs per passenger mile are expected to drop due to higher rates of asset utilization (Corwin et al., 2015), owning a personal CAEV is likely to initially be very expensive. Already, EVs are emerging onto the market with high initial costs due to their expensive battery components. In addition, CAEVs with high-cost autonomous components, such as high accuracy GNSS receivers costing £20,000 or more (Cui et al., 2017), would make for an expensive private purchase. As such, current UK CAEV development projects tend to focus on public transport applications, rather than on the potential for privately owned CAEVs (CCAV, 2020, CCAV, 2018, CCAV, 2017). Internationally, CAEV development and implementation are expected to have positive economic impacts; providing opportunities for new challenges, employment and creating a thriving global environment of healthy competition across transport industries (Meyer, 2018).

The use of batteries as a power source for CAEVs will reduce traffic congestion, noise and particulate pollution at local community levels and reduce the associated transport health risks for the local pollution (Leech et al., 2015, Vaidya and Mouftah, 2020). As well as the reduced local air pollution as a result of EV technology, CAEV ride-sharing services will further improve total transport system fuel economy (West and Howell, 2016), further contributing to reduced congestion. As CAEVs continue to develop, energy demand will drop due to the lighter weight of CAEVs, further propelled by more compact, efficient, and environmentally friendly powertrains (Corwin et al., 2015). At a wider scale CAEV's will reduce transport contributions to national greenhouse gas (GHG) emissions (Alkheir et al., 2018). In addition, the efficiency benefits of automation and connectivity are also able to contribute to reduced energy use. With UK energy supplies increasingly provided by renewable energy sources such as wind energy, the environmental impacts of CAEVs will continue to decrease.

Whilst the environmental benefits of CAEVs are more clearly defined for urban areas, the environmental benefits in rural areas are rarely considered despite the natural rural environment being arguably more susceptible to damage (Leech et al., 2015, KPMG, 2019, Vaidya and Mouftah, 2020).

2.9 The Urban-Rural CAEV Divide

Despite the specific rural challenges referenced, studies on CAEV implementation in rural communities and on rural roads is limited, with the majority of the literature focused on urban CAEV implementation and associated infrastructure challenges. As such, it is expected that the epicentres of transport's transformative change regarding CAEVs will be in urban rather than rural centres (Bosworth et al., 2020).

In October 2017 the CCAV presented a summary of 52 current and upcoming UK CAEV research and development projects (CCAV, 2017). Most of these projects focused on one or more of the critical CAEV development areas of positioning, mapping, or connectivity. In 2018, the CCAV produced a second report including 31 additional CAEV development projects (CCAV, 2018). Of the total 83 projects outlined in these reports, 23 involved real-world road testing. Further investigation into these projects found that six of the 23 real-world tests were conducted across both rural and urban environments, 16 solely in urban areas, with only one in a specifically rural environment which focused on off-road agricultural activity. The remaining 60 projects did not involve physical road testing but focused on developing CAEV hardware, software and other technologies, in most cases development included the simulation of use in an urban area.

This investigation highlighted that:

- Most CAEV development projects focused on the modelling of internal components and software for CAEV positioning and connectivity, rather than developing physical test vehicles - perhaps due to the early stages of CAEV technology at the time;

- From the 23 test projects, only seven involved an element of rural testing although six of these projects stemmed from urban centres originally and tended to focus on city-to-city journeys and lacked extensive integration of rural road types.

The CCAVs latest publication demonstrates the current state of UK CAEV research, development and testing (CCAV, 2020). Table 2.1 reviews the projects featured in the CCAV publication extracting projects that are specifically trialling CAEVs in real-world conditions. The review highlights a continued bias towards urban-based CAEV testing in the UK, with the CCAV promoting urban-based projects in particular. There are no specifically rural trials mentioned in this report.

Table 2.1 Rural review of real-world UK-based CAEV road testing projects in 2020

Project	Description	Urban or Rural
Aurrigo AutoDrive Pods	Designed to transport people efficiently on the last stage of their journey from transport hubs to their destinations. Initially implemented in Milton Keynes but currently working with Blind Veterans UK and the visually impaired in Brighton.	Urban
Five	Live trials of automated Ford Mondeos in London.	Urban
MOVE_UK	Automated driving research project focusing on addressing the issues of validation of automated driving systems.	Mixed
Oxbotica and DRIVEN	Demonstrated the capabilities of a fleet of self-driving vehicles in London's complex urban environment.	Urban
Smart Mobility Living Lab	Public and private London roads and digital and real-world testing.	Urban
CAVWAY	Fixed junctions and high-speed tests using slip roads onto motorways.	Motorway
CAV Forth	12-month trial of automated buses on Scottish roads seeing full-size, 12m, single-decker buses operating at a high level of autonomy along a 20km route that crosses the Forth Road Bridge.	Motorway
Venturer	This project trailed the safe user-led adoption of CAV technology by systematically assessing road users' responses to the introduction of driverless cars, using a series of increasingly complex scenarios.	Mixed
Streetwise	This project developed technology to demonstrate how electric, automated vehicles could provide a commuter service between Croydon and Bromley.	Urban
Human Drive	Consisted of a successful 230-mile automated journey across the UK through live traffic and natural conditions. The project contributes to the development of human-like self-driving.	Mixed
UKCITE	This project involved equipping over 40 miles of urban roads and highways with a combination of multiple wireless technologies, enabling seamless connectivity across the corridor.	Urban and Motorway
A2/M2 Connected Corridor	This 'connected corridor' links London to the port of Dover and beyond. It trials technology that will enable vehicles to communicate road safety information using roadside equipment and test connective technology on a variety of roads.	Mixed

It is important that the benefits of CAEVs are not just experienced by those living in urban areas, especially as it is rural communities who currently lack effective public transport and who are at most risk of severe traffic accidents. Rural communities may in fact have the most to gain from CAEV development and implementation and as such rural priorities and characteristics should be central to future CAEV developments. This would help to integrate CAEVs and ITSS nationwide and ensure that rural communities are not left behind, as they have been historically with transport systems and digital infrastructure.

This thesis's hypothesis that current CAEV testing is too urban-focused and that there is a need to consider and carry out CAEV testing in rural areas is affirmed by a report published by UK The House of Lords Science and Technology Select Committee, compiling thoughts from industrial and academic experts as well as from government officials regarding the future direction and development of CAVs. (Murphy et al., 2017).

2.10 CAEVs as a Rural Transport Solution

This chapter has highlighted the potential of CAEV technologies to fill the rural transport system gaps identified in Chapter 1. CAEVs can be an effective transport solution capable of addressing the accessibility, safety, digital connectivity and sustainability challenges faced by rural transport systems. However, their success will be reliant on contextual understanding and rural-orientated research, testing and implementation.

Further to the themes addressed in Chapters 1 and 2, conclusions from the Future of Rural Mobility Study (FoRMS) (Midlands Connect, 2020a) suggest that additional rural issues such as the lack of transport options and employee recruitment and retention can be addressed by the following:

- Use of technology in mobility services;
- Provision of comprehensive mobile internet coverage;
- Superfast broadband and 5G;

- Different funding and delivery models or public transport and service provision.

As this chapter has shown, each of the above points can be directly related to the potential of CAEVs, further indicating the need to explore rural CAEV implementation more seriously and thoroughly. Therefore, the following chapter describes investigative research which explores the technological and infrastructural practicalities and challenges of rural CAEV implementation, specifically addressing autonomous and digital functionalities.

3 RURAL CAEV IMPLEMENTATION CHALLENGES

There is a lack of clarity as to the infrastructure needs of CAEVs, particularly at the current speed CAEV technology is progressing. There is therefore a need to understand the situations that might be the most technologically and infrastructurally challenging for CAEVs, so that CAEV-infrastructure planning and design standards can be developed with clear purpose (TSC, 2017). In a study addressing a broad range of CAEV challenges the most cited challenge was that of public acceptance, followed by infrastructure, and then policy and integration (Fleming et al., 2017b). Further down the list were CAEV technologies and cyber security, areas where many CCAV UK projects currently focus (CCAV, 2020, CCAV, 2018).

Through a combination of literature review and primary practical experimentation, this chapter explores the challenges facing rural CAEV implementation. Experiments were carried out to measure the relative availability and reliability of three technological and infrastructural CAEV implementation challenges in detail. Satellite positioning, the readability of roads, and digital communications are all crucial requirements for effective CAEV implementation both as individual and integrated technologies. In addition to these technological and infrastructural challenges, other challenges based on human and institutional perspectives are explored in the final part of this chapter.

The primary experimental trial in this chapter was conducted in 2018 around the city of Nottingham, UK; a convenient location for urban-rural CAEV positioning and communication testing and comparison, with a busy but relatively small city-centre close to rural areas south of the river Trent. The trial survey van was driven manually, and positioning equipment was used to determine the position of the van. At no point was the survey van autonomous. Data from two previous trials carried out by the Nottingham Geospatial Institute (NGI) in 2017 and 2016 was also used to affirm and build on the findings of the 2018 trial. The results discussed in this chapter combine data from all three trials to encompass a broader range of positioning accuracies and traversed environments. The results from these trails are used to explore satellite positioning and road readability challenges for CAEVs. Additional trials conducted using smartphones both on foot and by bicycle explore the potential digital communication challenges faced by CAEVs.

The number of trials conducted were limited, in the early stages due to resource availability and timetabling, and later due to the COVID-19 pandemic. Ideally, each route, both exploring satellite positing and digital connectivity availabilities would have been carried out several times each to achieve more reliable and repeatable results. This would have provided a greater representative range of driving and infrastructure conditions and generated more significant results. In their current form, the results are limited in their reliability.

3.1 Satellite Positioning

Vital to a CAEVs autonomy is the ability to position itself both geographically (absolute positioning) and relatively to its surroundings. For CAEVs to navigate safely, real-time vehicle positioning, dynamic connectivity and mapping are three of the key technologies required (Stephenson et al., 2013a). To ensure the most extensive and effective real-time positioning capabilities are achieved, CAEVs should use the Global Navigation Satellite System (GNSS) and integrate sensor technology, such as Inertial Navigation Systems and cameras, to ensure positioning reliability. When these technologies are combined, GNSS positioning primarily determines the CAEV's absolute position, whilst sensors determine the CAEV's relative position in its surrounding environment and to other vehicles. When GNSS fails, sensors can provide a temporary positioning solution until GNSS connectivity is re-established.

Navigation solutions can be improved by collaborative networks. In the UK, a network of static GNSS reference stations, known as CORS (Continuously Operating Reference Stations), enable CAEVs to use network real-time kinematic (NRTK) GNSS positioning across the country. When available, this technique improves positioning accuracy by sending corrections over cellular networks and allows CAEVs to travel greater distances without mobility constraints, compared with Single Point and Differential GNSS positioning techniques (Aponte et al., 2014). NRTK can deliver 5 cm accuracies or less. This level of accuracy is required for the safe navigation of CAEVs on UK roads. However, the strength of the communication signal between the moving CAEV receiver and the stationary network reference data server can fluctuate. Whilst the UK's mobile-internet network is extensive, there are some areas that remain poorly connected and reliable NRTK positioning requires consistent coverage which cannot be guaranteed by current national digital infrastructure. Further significant barriers to NRTK positioning include data loss and message delay (Stephenson et al., 2014), but also physical GNSS signal obstructions. In urban areas, these obstructions are obvious in the form of high-rise buildings or smaller buildings and infrastructure which cause roads to be less exposed. In rural areas, obstructions are less obvious but can take the form of trees or bridges and other infrastructure.

Through the vehicle trials introduced at the start of this chapter, this section validates rural GNSS positioning performance for CAEVs. Whilst CAEVs will ultimately fuse sophisticated GNSS and sensor technologies, this chapter addresses GNSS and sensor performance separately in a rural context, in contrast to urban environments.

3.1.1 Methodology

All three road tests used NRTK positioning techniques to define the vehicle's position for every second of each journey. These NRTK data were analysed to replicate the techniques that CAEVs would likely use when implemented on rural UK roads (Aponte et al., 2014). NRTK is the only absolute positioning technique that provides the active control accuracy required (<0.1m) for CAEV positioning up to Level 5 autonomy, which V2X applications also rely on (Cui et al., 2017, Stephenson, 2016). Maintaining these high accuracies consistently is vital for the safety of occupants and road users and therefore the results define the 'fix' level as the only reliably accurate level of NRTK positioning. Whilst accuracy quality varied throughout each test, only the data points within 0.1m accuracies are deemed accurate enough for safe rural CAEV operation. Anything other than this level of accuracy is deemed incapable of safe positioning and the NRTK positioning is termed to have 'lost fix'.

The equipment was used to determine the position of the test vehicle, via GNSS NRTK positioning, across a variety of environments, from built-up urban, to open-air, through to dense tree-covered rural environments, to see if and how positioning quality and accuracy changed.

Three types of positioning device were used:

- Leica GS10: This survey grade receiver was used to collect raw positioning data only. The Leica GS10 internally processes positioning data to produce high quality results. This receiver is at the top end of the range costing around £15,000. The high-quality results from this receiver were the most appropriate for this experiment as the aim was to determine positioning quality based on location, rather than the equipment quality.

- Javad Triumph LS: This is a similar quality receiver to the Lecia GS10 and costs around the same price. In this trial, whilst the Leica GS10 collected high quality raw data, the Javad operated in GNSS NRTK mode and used the national SmartNet CORS network, with support from the accompanying car, to apply NRTK corrections to the data during the test. NRTK can provide higher accuracies than single receivers providing that there is a local network receiver (Aponte et al., 2014).

- U-blox M8: This is a single frequency receiver which does not provide the quality of the Leica and Javad receivers. However, it is very low cost and can provide accurate enough data to make meaningful comparisons with the higher cost receivers.

Using three devices helped to authenticate the results of the Lecia GS10, reinforced result accuracy and highlighted gross errors. Accompanying equipment included physical and digital copies of the test route; SIM cards and mobiles for 3G/4G connectivity; DSRC and cellular modules for experimental V2X communication; and a dashboard camera to record the route and environment types in real-time.

The complete experiment setup is illustrated in Figure 3.1. By aligning video footage with position data points post-trial, the hypothetical capability of relative sensors could be assessed. This method also revealed how infrastructure, signage and road surface conditions varied across environments.

Using the urban-rural Lower Layer Super Output Area (LSOA) geographic classifications around Nottingham (Bibby and Brindley, 2016, DEFRA, 2016), a route was determined that passed along a range of rural road types and environments to get a diverse spread of location types. However, as these classification zones are based on population alone and don't account for road type, the route was refined by exploring road types and condition, as defined in Chapter 1, in each zone using Google Maps and Google Street View. Different road types, marking density (Table 1.1), marking quality (Table 3.1) and local environments (Figure 3.6) were explored, and the route was refined to accommodate as many different roads and environments as possible. Figure 3.2 shows the final route used for the road test.

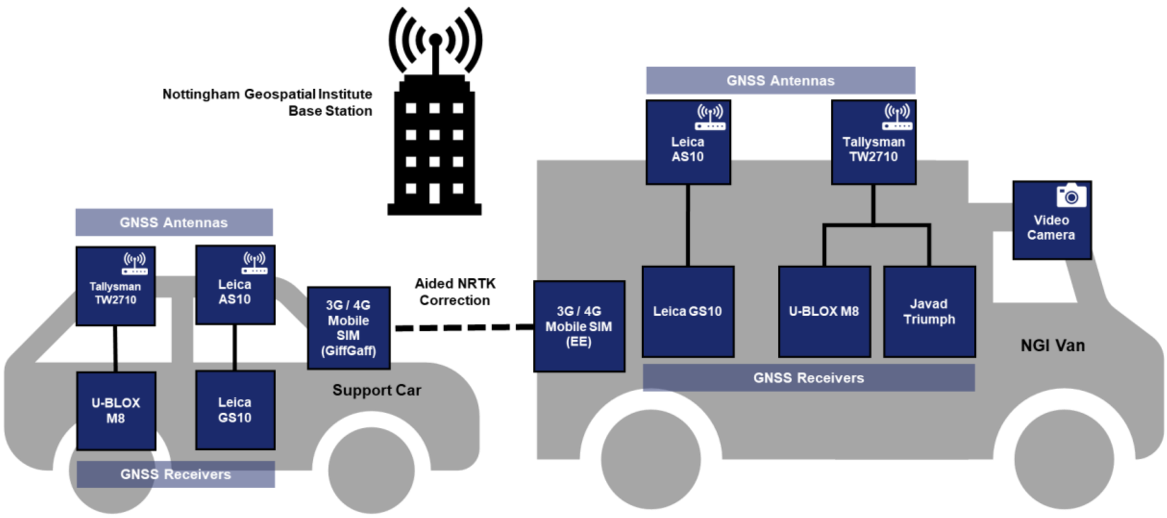


Figure 3.1 Vehicle experiment setup (2018 trial)

Data from the Javad and Leica receivers were automatically processed by the receivers in real-time. The purpose of this experiment was to determine how the raw positioning quality of these receivers varies across environments and so post-processing and manipulation of the data, to remove large errors for example, was not conducted. However, post-interpolation of the Javad results was required to align positioning timings. The Javad receiver was set to record every 0.2 seconds starting from every 0.0 second (0.0, 0.2, 0.4, 0.6, etc…). However, due to an internal hardware error, manufacturer related or otherwise, the Javad receiver recorded every 0.2 seconds from every 0.1 second (0.1, 0.3, 0.5, 0.7, etc…) as shown in Figure 3.3.

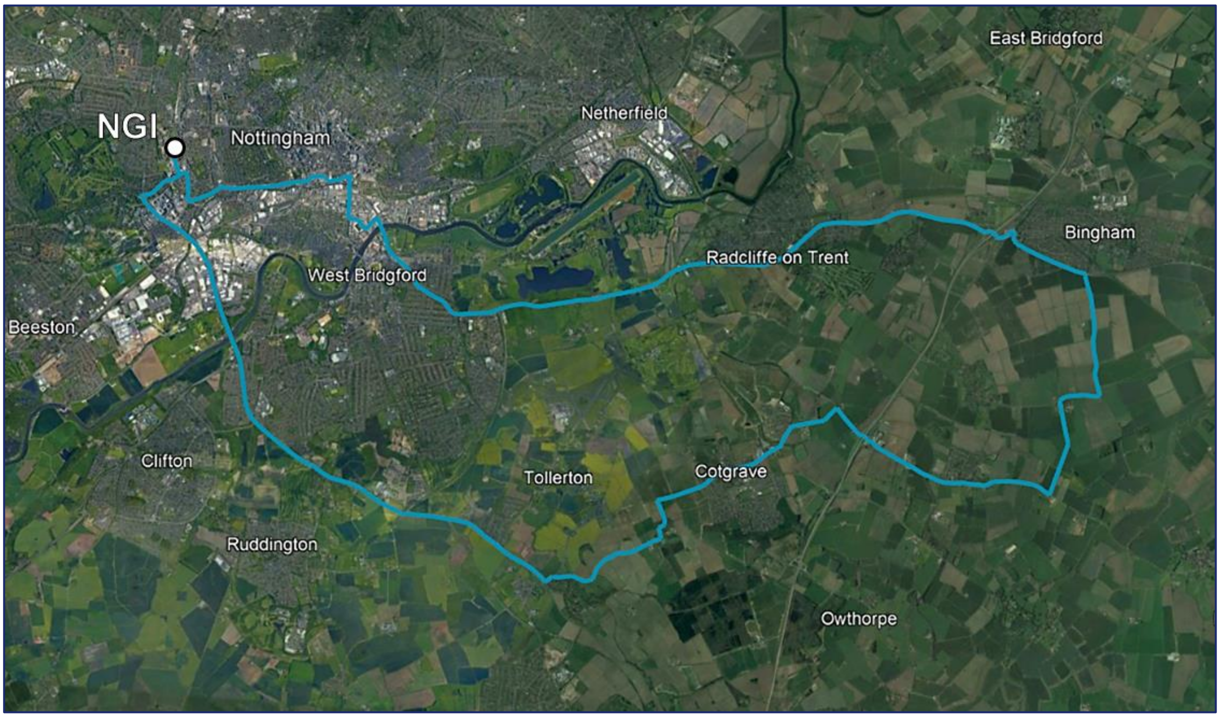


Figure 3.2 Road test route (2018 trial)

2018-03-13, **14:13:34.100**, 52.9519521227, -1.1834515894, 80.572

2018-03-13, **14:13:34.300**, 52.9519521222, -1.1834515965, 80.570

2018-03-13, **14:13:34.500**, 52.9519521173, -1.1834515824, 80.572

Figure 3.3 Javad unsynchronised timings (2018 trial)

Whilst analysing the results, the video recording of the route during the experiment was found to be out of sync with the satellite positioning data points. To determine this time disparity, distinct positions on the GNSS point data map, such as sharp corners or wrong turns, were compared to the same positions on the video. Figure 3.4 shows this process. From a comparison between ten position points, the time lapse was found to be 24 seconds, which was both the mode and mean value from the results. Once this time was found the data points and video locations could be aligned and the discrepancy resolved.

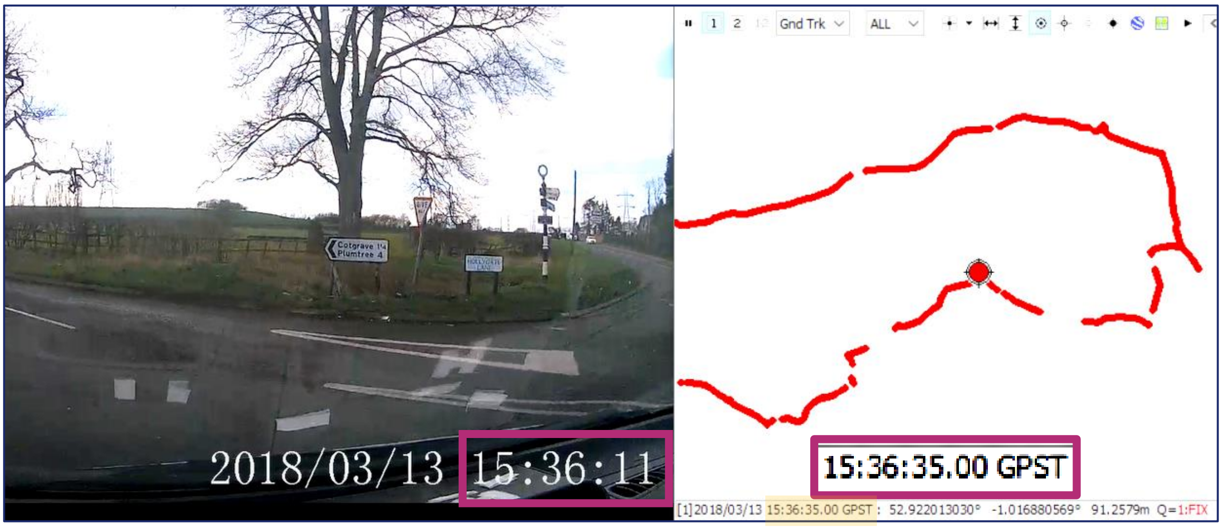


Figure 3.4 Time synchronisation comparison (video footage and GNSS data)

Figure 3.5 Fix point data (2018 trial)

The raw data from the GNSS receivers was viewed visually using RTKPLOT software. RTKPLOT is an open-source software package that enables the plotting of GNSS observation data for analysis. RTKPLOT displays position, velocity and acceleration data as well as the number of satellites in sight, their constellations and orbits. All of these data were associated with a single second in time. The RTKPLOT software was primarily used to determine the positioning fix accuracies at different points along the route as well as those portions of the route that lost fix. By superimposing the results from RTKPLOT into Google Earth, the precise locations where the vehicle lost GNSS NRTK fix could be pinpointed (Figure 3.5). From there an analysis of the environment and road conditions was undertaken to determine the reasons for the loss of fix at these points, as well as the consequences of this loss in relation to the environment.

3.1.2 Results

Based on the rural and urban road definitions defined in Chapter 1, the qualitative categorisation of road environments in terms of GNSS positioning capability, and in relation to the overhead cover density, enabled the numerical analysis to determine which environment types lacked effective positioning capability.

Road environment definitions were needed to distinguish between open space, light cover and dense cover. Figure 3.6 subjectively defines the distinctions between the three rural density definitions. Intuitively, dense environments suffered the greatest amount of GNSS NRTK fix loss; light environments suffered slightly less than average loss in urban environments but greater than average loss in rural environments; and open space suffered the least fix loss, although more than might be expected at 14.5% of the travel time in open space environments. Generally, the denser the environment, the more the obstructions, and the greater the chance of fix loss (Figure 3.7). These loses are ultimately due to the physical obstructions in the surrounding environment, be they trees or buildings, that cause the GNSS receiver to lose lock on the GNSS. 62% of rural road time was spent under open sky and 83% of urban road time under building cover (Figure 3.8).

Figure 3.7 shows the proportions of fix loss in each environment density for rural and urban roads. Both urban and rural roads follow the same pattern of fix loss with dense environments experiencing the most loss, but with rural environments showing more extreme jumps between densities. There is doubt over the high 95% figure for dense rural cover due to the vehicle only being in this environment for a total of 2 minutes and 57 seconds. This may not be a long enough time to collect reliable data, relative to the other environment types in which the vehicle spent greater periods of time. However, based on the trend that can be identified in Figure 3.7, a value greater than the dense urban value of 51% is likely.

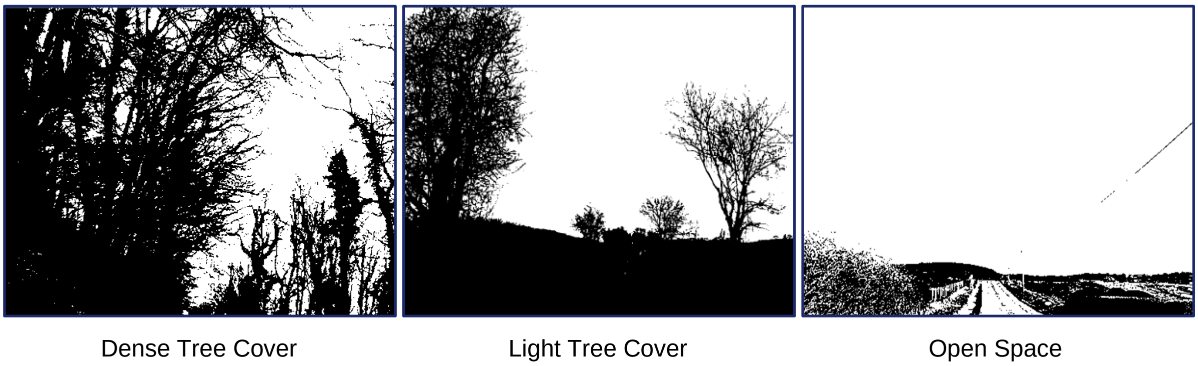


Figure 3.6 Rural environment density distinctions (examples 50% black and white contrast photographs)

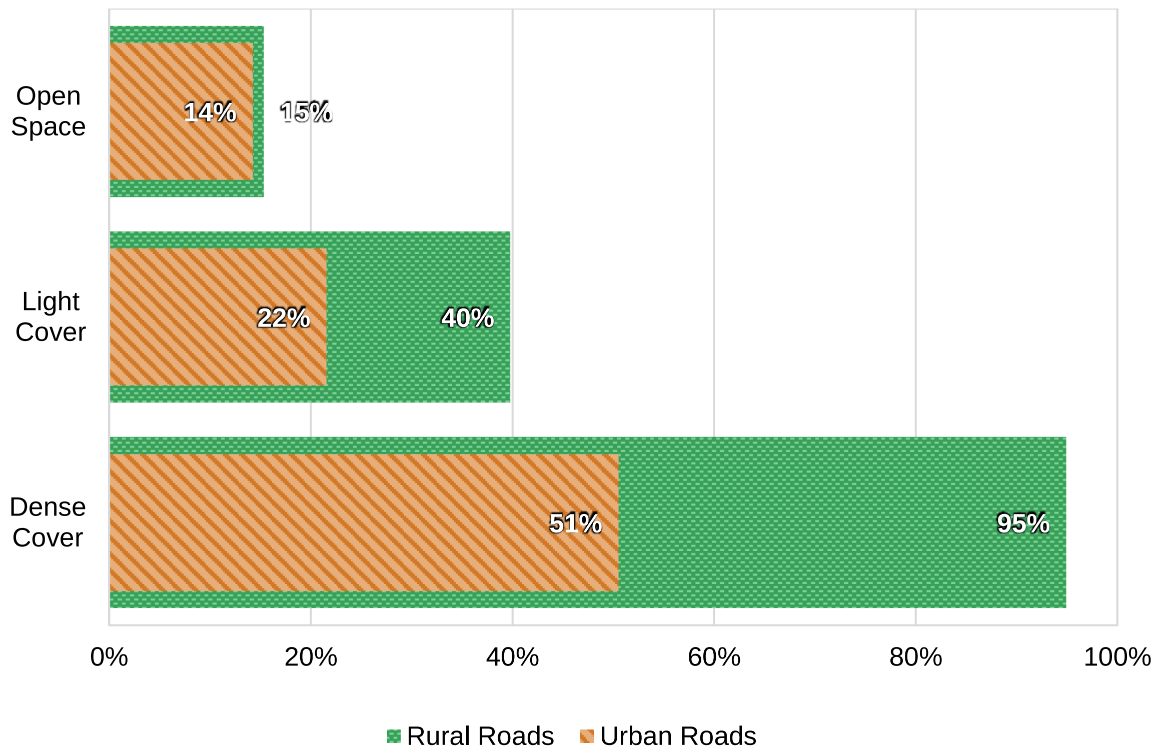


Figure 3.7 Fix loss by environment density, rural-urban comparison

What is clear from these results is that environments categorised as 'dense' have the greatest effect on positioning quality due to proportionally experiencing the greatest fix losses (Figure 3.7) which occur when the GNSS receiver on the vehicle loses direct sight of GNSS satellites above due to dense and frequent obstructions. The denser and more frequent the obstructions, the fewer satellites the receiver remains in contact with and therefore the less accurate the positioning of the vehicle. However, it is also important to realise that densely covered environments are the least encountered and so the loss of fix is not as frequent as Figure 3.7 might imply.

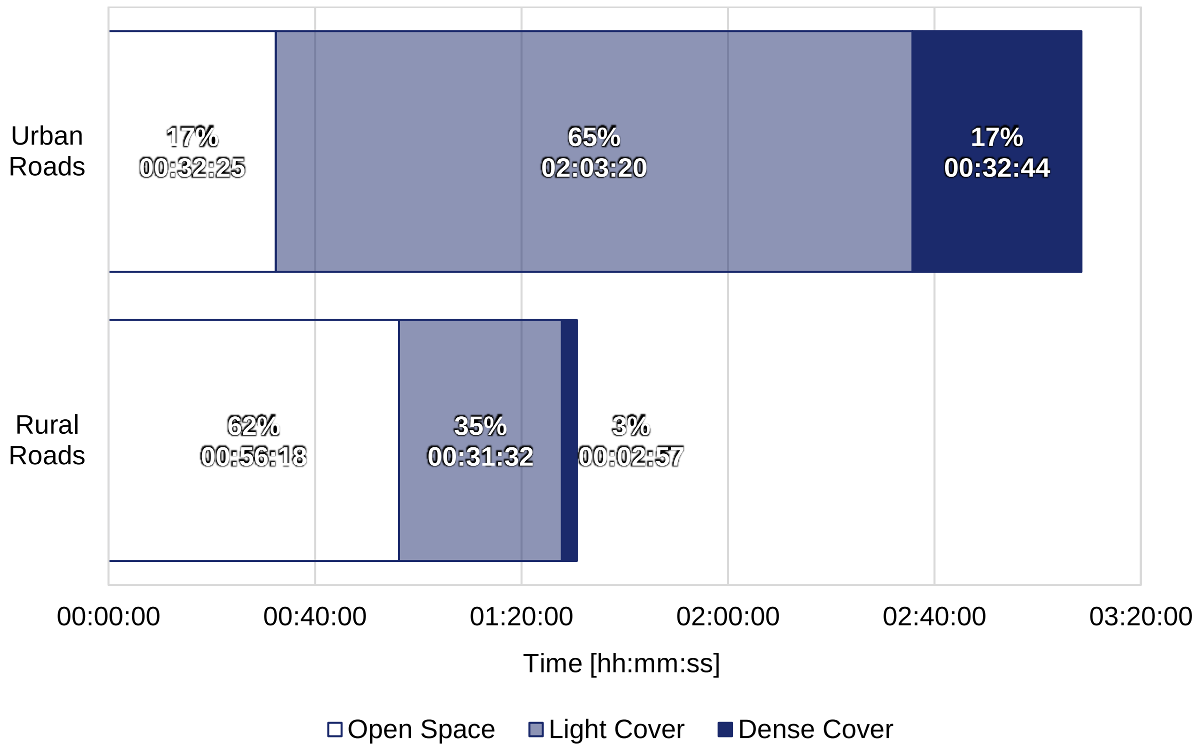


Figure 3.8 Cumulative time spent on urban and rural roads over the three trials, split by environment density

In relation to rural roads specifically, whilst both urban and rural fix loss increases with environment density, the loss of fix is proportionally dominant on rural roads (Figure 3.7). However, the average loss for both rural and urban roads is approximately the same; 26% and 25% respectively. The contrast between rural and urban fix loss and environment density in Figure 3.7 is therefore skewed by the length of time spent on rural roads being half of that on urban roads, as well as due to the short amount of time spent on densely covered rural roads (Figure 3.8).

Due to the nature of GNSS positioning, physical obstructions will always be a barrier to consistent and accurate positioning. This is a major reason as to why CAEVs should not solely rely on GNSS positioning for navigation and should integrate sensor technologies to increase positioning reliability, through relative positioning, until absolute positioning can be re-established. However, where some areas may lack sufficient GNSS connectivity, others may lack the infrastructure quality required for the effective use of sensors such as cameras. Therefore, more work needs to be done to ensure both these are improved simultaneously across all environments.

3.2 Unreadable Roads

Sensor technologies enable CAEVs to effectively visualise their surroundings. The primary purpose of this is to prevent collisions and to help CAEVs understand the changing environment around them. CAEVs use a combination of sensor technologies including range detection sensors, such as radar and LiDAR, that determine where other objects are in relation to the vehicle; and visual sensors, such as cameras, which can detect fine details and colour. Cameras, with the help of software, can perceive objects and read traffic signals, road signs and markings, allowing the CAEV to identify hazards and make any necessary positional adjustments. These sensors and cameras continuously monitor the local environment 360 degrees around the vehicle. However, cameras are susceptible to changes in environmental conditions, particularly those due to weather and light. No CAEV has yet been able to demonstrate the same reliability in extreme weather conditions as in typical conditions (Milford and Roberts, 2017). Whilst sensor technology enables relative localisation and environmental perception on its own, it can be effectively integrated with absolute GNSS positioning. Clear road markings are an essential component of road infrastructure (TSC, 2017) and in this study, the ability to read road markings and features is assumed pivotal for safe relative CAEV positioning and localisation on roads, otherwise CAEVs must rely solely on the absolute positioning provided by GNSS. CAEVs are expected to be unable to read road markings that are significantly deteriorated, unusual, non-standard, inconsistent, obscured, or lacking completely (EuroRAP, 2011, King, 2013, TSC, 2017).

EuroRAP define a good road line marking, using the Europeans Road Federation's definition, as one with which the…

> *"…minimum performance level under dry conditions is 150 mcd/lux/m² and which has a minimum width of 150 mm for all roads; for wet conditions, the minimum performance level should be 35 mcd/lux/m²."*

King, 2013: page 7

However, the current widths of UK markings range from 100mm to 200mm depending on use and location(Anonymous, 2017c) and therefore don't all currently meet this definition.

3.2.1 Weather Effects

Whilst not explicitly analysed as part of the vehicle trials, weather can have a serious effect on the quality of CAEV sensing capabilities. Figure 3.9 looks at photographic examples of UK weather and illustrates some of the extreme effects of weather on rural and urban road networks and how these are likely to affect relative CAEV navigation. The road markings shown in the photographs in Figure 3.9 cannot be compared with the suggested EuroRAP road marking standards without further study. However, assuming they do meet the required performance under dry conditions, given that they appear to be relatively well maintained, Figure 3.9 indicates that the required performance may not be met under different weather scenarios including snow and rain.

Figure 3.9 Weather effects on road surfaces

- Snow: This photograph in Figure 3.9 shows a small urban estate road in Nottingham. Not only does the snow obscure any road markings but also urban features such as pavements and drainage features. Whilst these features would usually act as guides for navigation, the snow completely obscures them, making the road unnavigable by sensors and reliant on satellite positioning. Whilst major urban roads are gritted to prevent snow cover, minor roads like this one are not a priority, however, although not subject to heavy traffic flows, these types of roads are journey destinations and will be encountered by future CAEVs. Heavy snow will be a particular problem on small rural roads in the UK.

- Sun: Glare from the sun can cause problems for on-board sensors and cameras. Glare is usually the result of a bright low sun and clear sky and can reduce the visibility of road features, particularly at long distance. Glare is particularly disruptive after rain as wet surfaces reflect and enhance the effects of glare and can disguise road markings.

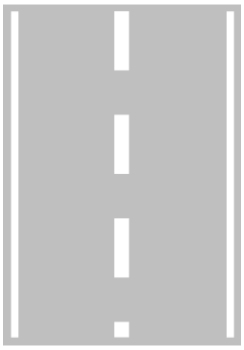
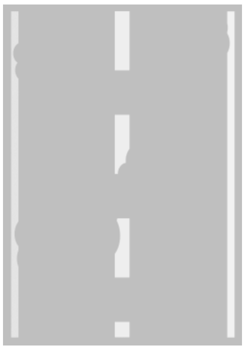
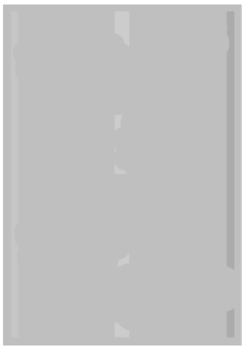
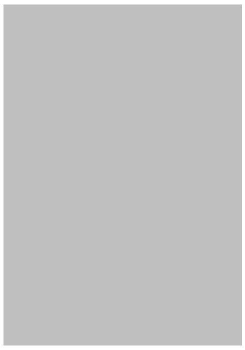
- Rain: These two photographs in Figure 3.9 show the same road but in different directions in different weather conditions. In dry weather the road markings and road features are clearly defined. However, in wet conditions the markings are much harder to define and bright reflections on the road surface could confuse CAEV on-board sensor and camera technology.

- Road condition: All of the photographs in Figure 3.9 were taken in the UK in March 2018 during a cold stormy period colloquially referred to as 'The Beast from the East'. This final photograph highlights a major effect of the range of weather conditions on roads. After the storm, pothole related incidents doubled in the UK. The Royal Automobile Club (RAC) suggested that poor road conditions before the storm amplified the problem of potholes (Horton and Marshall, 2018).

3.2.2 Methodology

The data for this section was collected during the 2018 road trial. During this trial, the road environment and road marking conditions were recorded for each section of road that was travelled along using the road mark density definitions in Table 1.1 and the road mark quality definitions in Table 3.1. This analysis method assumed that each stretch of road would have been and will be maintained as one entity and to the same standard. However, this is unlikely to be the case for longer roads and where appropriate these were split into manageable sections for data analysis. Similar processes for the two other road tests were carried out but using Google Earth satellite imaging and Google Street View photography. However, this method meant that the road conditions and environment were not recorded at the same time as the experiments were carried out, and there was no video recording from either test. Nevertheless, it can be assumed that road conditions are unlikely to change drastically over the small periods (a few years) between the trials and the time Google photos were taken.

Table 3.1 Road mark quality definitions

Category	Heavy	Medium	Light	None
Description	Bold and defined road marking with little to no signs of wear or fading.	Some wear and fading but markings are still recognisable.	Evidence of past markings but are no longer recognisable - includes blacked out markings.	No road markings.
Diagram				
Example				

3.2.3 Results

This study defined an 'unreadable' road as one which either has no road markings, or roads where the markings were faded to the extent to which sensors would be unable to accurately detect them. Rural examples of such unreadable roads are shown in Figure 3.10. Based on the footage recorded by the vehicle dashboard camera, every urban road travelled had either heavy or medium density road markings displaying lane, roadside and junction information. Of these urban road markings, less than 4% were faded to an unreadable standard. The majority of rural roads travelled had either minimal lane markings or no markings. In the rural case, less than 3% of marked roads were faded to an unreadable standard, however, 16% had no road markings whatsoever. Therefore, a total of 19% of rural roads were unreadable, with 60% having minimal markings. These findings support the definitions for rural and urban roads defined in Chapter 1.

Faded Marked Rural Road

Unmarked Rural Roads

Figure 3.10 Unreadable rural roads (example photographs)

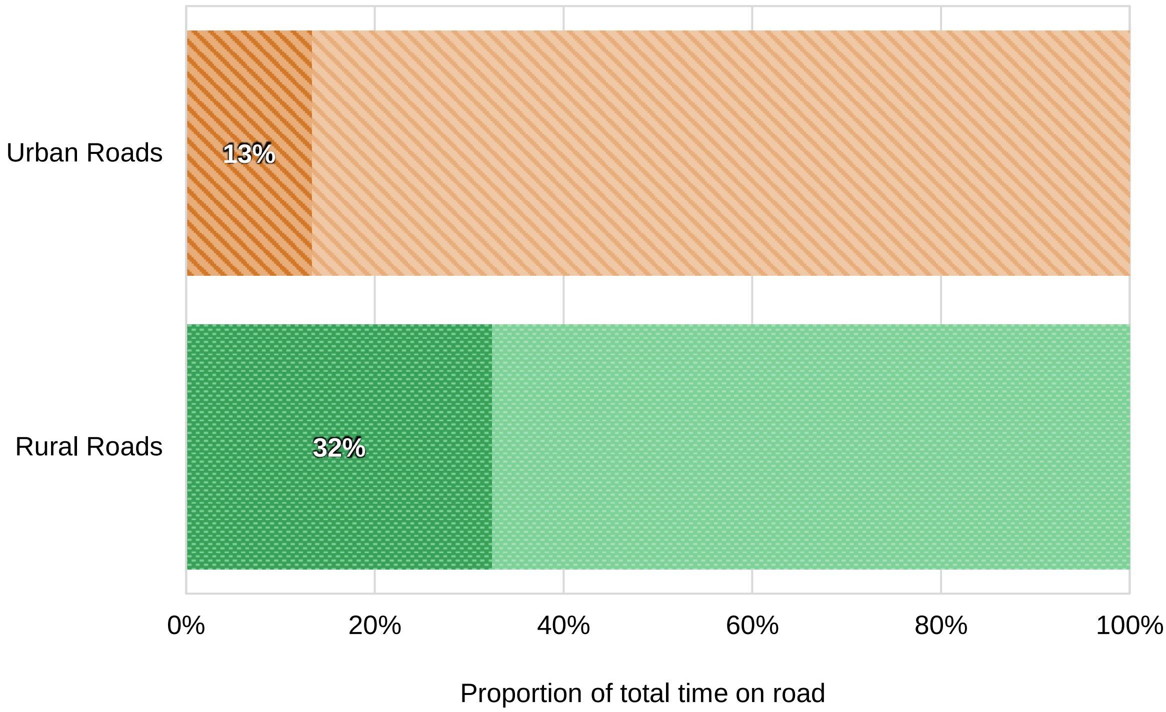


Figure 3.11 Proportions of fix-loss on unreadable roads, rural-urban comparison

Disproportionately, more unreadable roads were encountered on rural roads than urban roads, despite the time spent on urban roads being over double that of the time spent on rural roads (Figure 3.8). Sixteen minutes and 14 seconds were spent on unreadable rural roads compared to seven minutes and seven seconds on unreadable urban roads. Referencing the satellite positioning results earlier in this chapter, of the time spent driving on unreadable roads, rural environments suffered greater proportional fix loss than urban environments (Figure 3.11). This is significant as it shows what proportion of the time the vehicle on roads that lack any markings, or with markings that were not clear enough to read, lost fix on NRTK positioning and therefore lost accurate positioning capability.

3.3 Digital Communications

A CAEV's positioning capabilities can be further supported by wireless connectivity which can be used to provide data on position when other techniques, such as satellite positioning and on-board sensing, fail. Communication technologies are important for CAEV V2X capabilities to support positioning, perception, and therefore vehicle safety. For example, satellite positioning correction data can be provided to the vehicle via digital communications to support, correct or re-establish GNSS positioning services (Stephenson, 2016).

As reviewed in Chapter 1, rural mobile and broadband coverage is often inconsistent, however, reliable communication capabilities are important for effective CAEV operation including the ability to share information between vehicles and for demand responsive transport (DRT) functionality (Midlands Connect, 2020a). Referencing the weather and sensor analysis in Figure 3.9, camera sensing technology can underachieve in harsh weather conditions. However, V2X cooperative technology can take the experience of cars ahead to warn oncoming vehicles of difficult surfaces or changes in weather. This provides all CAEVs with enhanced situational awareness so that they, and their drivers, can be better prepared for changing driving conditions due to weather events(Stephenson et al., 2012).

For this part of the study, investigations were carried out into two types of communication technology. The first, cellular connectivity, was explored using 4G mobile communication with smartphones which use similar connectivity technologies as CAEVs. The second, DSRC, is a short-range communication technology specifically developed for CAEVs to communicate with each other. Both these technologies were tested in rural scenarios to establish their rural capabilities and identify the digital communication challenges for rural CAEV implementation.

3.3.1 4G Cellular – Methodology

The following mobile data trials were conducted using smartphone 4G technology. 4th Generation (4G) is an extension of 3rd Generation (3G) wireless technology, which itself was developed to meet the International Mobile Telecommunications 2000 (IMT-2000) standards set for wireless communication speeds. Beyond these standards demand has motivated the development of 4G and Long-Term Evolution (LTE) wireless technologies to improve data rates and quality of service. 4G is currently the long-term dominant wireless communication technology in the UK. LTE wireless technology was developed in parallel to 4G and now contributes to 4Gs potential. 4G LTE provides full mobility of high speed data rates and high capacity services while maintaining full backward compatibility (Akyildiz et al., 2010, Singh, 2016). The data rates and service capabilities of 4G LTE mean that it is seen as a critical technology needed to aid effective CAEV operation (Gowling WLG, 2018, Malek, 2012), particularly in rural areas where new high-speed 5th Generation (5G) wireless technologies are unlikely to penetrate due to the short-range nature of 5G infrastructure and the sparseness of rural roads and populations (Seymour et al., 2017).

4G quality can be measured in a number of ways including Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and Reference Signal Strength Indicator (RSSI). Both RSRP and RSSI have measurement units of decibel-milliwatts (dBm) and express an absolute value of power, whereas RSRQ has units of decibels (dB) and expresses a ratio between two power values.

The most basic 4G quality measurement is based on RSRP measurements which are used by connected devices to select which cell station to use at a given time, control handover between cells and for mobility measurements. RSRP is the average power received from a single cell specific Reference Signal Resource

Element (RE) (Redazione, 2017). The RE is the smallest time-frequency resource unit for wireless download or upload transmissions. However, transmissions are allocated in units of Resource Blocks (RB) which consist of multiple REs (Ahmadi, 2010). In the case of 4G LTE transmissions, each RB consists of 84 REs. Typical values for RSRP range from -75 dBm close to cell sites to -120 dBm at the edge of LTE coverage areas (Redazione, 2017).

The RSRQ is the measured power over the entire transmission bandwidth (BW) or occupied RBs, which provides a better measurement for transmission channel quality. The RSRQ also provides additional information when RSRP is not sufficient to make reliable handover or cell reselection decisions. The value range for RSRQ is -3 dB to -19.5 dB (Taufique, 2019).

Finally, the RSSI is measured over the entire bandwidth of occupied RBs (Redazione, 2017) and provides information about total received transmission power inclusive of interference and noise. RSSI is the most traditionally used metric to measure signal quality, having been used since it was introduced to measure 2G GSM performance (Taufique, 2019). As RSSI considers interference and noise due to environmental factors at and between transmitter and receiver, this is the quality measurement used throughout the following studies.

A range of open-source smartphone applications were considered and reviewed for use in the 4G cellular trials. Table 3.2 summarises the functions available with each application. The functions listed are those that were deemed necessary by the researchers to effectively conduct 4G cellular measurements and analysis.

Based on the analysis in Table 3.2, Net Monitor Lite was selected as the application used to monitor 4G cellular connectivity during the trials. In addition, Net Monitor Lite had a sister app called Cell Tower Locator which calculated the rough locations of cell towers by estimating the centre of cell tower service areas calculated by the app using the signal strength received.

Table 3.2 Assessment of smartphone cell monitor applications

Smartphone Application	Records RSSI	Records Latency	Records Location	Real-time measurements	Export function	Intuitive	In-app visualisations
OpenSignal	N	Y	Y	N	N	Y	Y
Meteor	N	Y	N	Y	N	Y	Y
Net Monitor Lite	Y	Y	Y	Y	Y	Y	Y
Cell Signal Monitor	Y	Y	N	Y	N	Y	N
RF Signal Tracker	Y	Y	Y	Y	Y	N	Y
Network Analyser	Y	Y	N	N	N	N	N

3.3.2 4G Cellular – 2018 Trial Results

Whilst performing the satellite positioning trials, accompanying equipment included SIM cards and smartphones for 3G and 4G connectivity and DSRC and cellular modules for experimental V2X communication. The results of the following analysis were obtained from the 4G enabled smartphone which was placed on the dashboard of the support vehicle during the 2018 trial.

The cellular connectivity test during this trial provided an insight into some of the communcaiton challenges facing CAEVs in rural areas. In Figure 3.12, the pink and blue points on the route highlight the points on the route with strong 4G RSSI and the red the weakest. There are large fluctuations all along the route but generaly Nottingham city centre to the north west is well connected whereas rural areas to the south of the route are less well connected. Missing from this data are the approximate locations of cell towers. However, based on these results it can be assumed that there are greater concentrations of cell towers towards urban Nottingham and fewer to the south and east rural areas.

Figure 3.12 Cellular connectivity quality (2018 trial)

3.3.3 4G Cellular – Bicycle Trial Results

Another 4G cellular test was carried out to the north-east of Nottingham by bicycle, incorporating rural roads and villages. The 4G enabled smartphone was strapped to the front of the bicycle. Unlike in a van, this smartphone had open air access to mobile signals, as a CAEV would likley have. Further, a bicycle travels slower than a van which ensured more time for the smartphone to generate reliable location-based RSSI readings.

The route was selected for its sections of rurally classified areas as defined by the RUC 2011 (Bibby and Brindley, 2013a), the rural road definitions in Chapter 1, and its proximity to a 4G cell tower. 43% of the route was contained within these rurally classified areas. Despite being classified urban, the sections of the test route outside of the rural areas looked to be just as rural in appearance mainly consisting of single tracked lanes between farmland. The sections of test route to the South and West within the rural zone passed through the populated villages of Cossall and the south of Awsworth, which appear less rural visually with the roads being two lanes. Photographs or video footage of the route would have been useful in explaining this and assisting in the analysis.

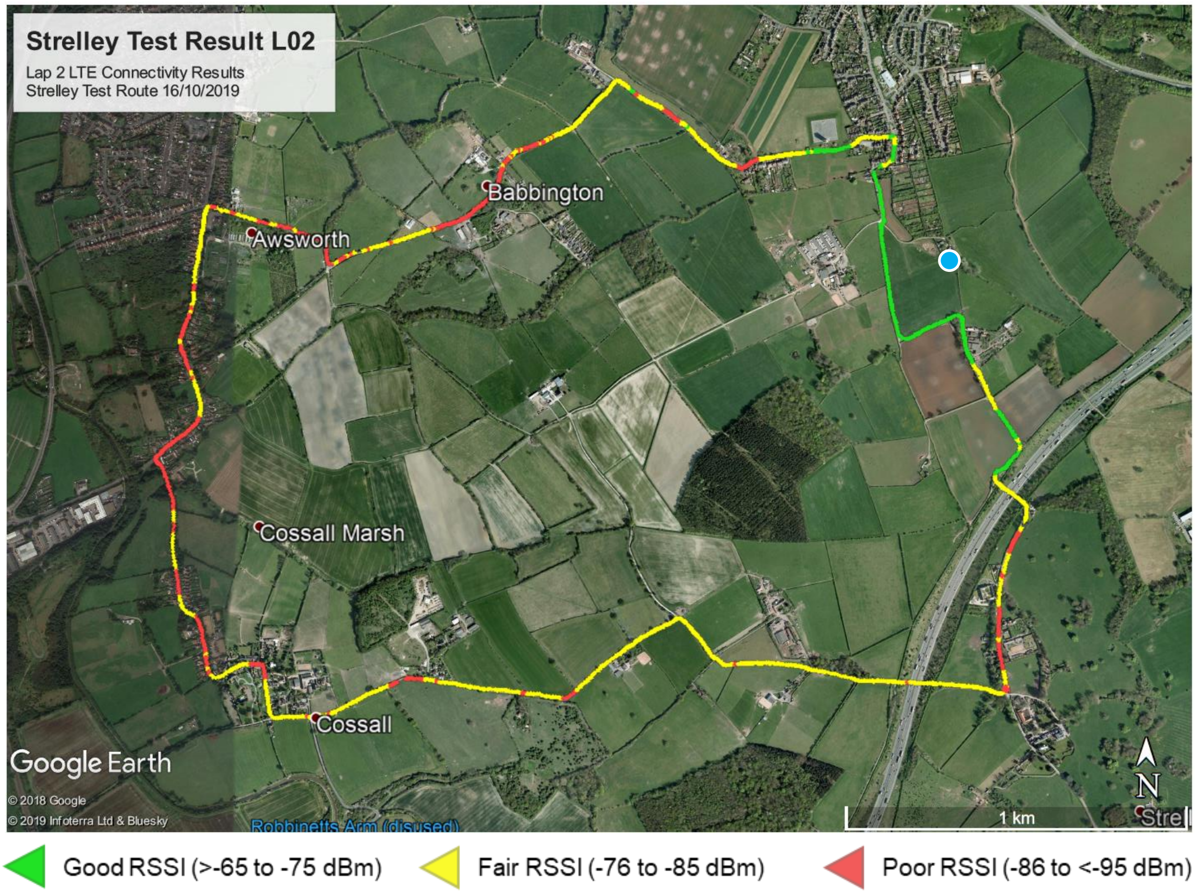


Figure 3.13 Cellular connectivity quality (bicycle trial)

Figure 3.13 shows the results of the trial with green regions showing strong connectivity, yellow moderate connectivity and red poor connectivity. The location of the 4G cell tower is also marked. The results show strong RSSI signal being received in the north-east portion of the route with poor signal in the south-east, west, and north-west regions. The distribution of strong-weak connectivity can clearly be related to the location of the cell tower. This cell tower is also located at one of the highest points along the route and looks over a large portion of the M1, the west of Nottingham and the large village of Kimberly to the north.

Figure 3.14 RSSI measurements - views from cell tower (bicycle trial)

Figure 3.14 shows images of the test route looking from the perspective of the cell tower using Google Earth's terrain and 3D buildings feature. What can be seen is that the sections of route in the foreground receive strong signal, reaching -65 dBm RSSI. The sections of route in the background are yellow and red, inferring that the distance is a relevant factor affecting the signal quality in the west sections of the route. It can also be noted that the red sections that are geographically closer to the cell tower are often partially obstructed by features such as trees and buildings, suggesting that these physical barriers also influence the signal quality in these areas.

3.3.4 DSRC – Methodology

The "Pi2X" DSRC transmitter and receiver modules used in these trials were developed and built by the CAV research group at the Nottingham Geospatial Institute in order to conduct V2V, V2I and V2X experiments and road tests. The DSRC trials in this study were conducted on foot and involved placing the DSRC receiver at a stationary location whilst walking with the DSRC transmitter. The receiver was placed at height designed to avoid potential signal obstructions due to local objects. The aim was to test DSRC communication capabilities in rural-like environments and scenarios by using hilly terrain and foliage as barriers to disrupt the DSRC line-of-sight signals.

Unlike 4G LTE cellular communications, DSRC communications require an absolute position in order for the transmitter and receiver to communicate data regarding their relative location. For these DSRC trials the modules used a U-Blox M8 GPS receiver to collect their absolute position data. Following a number of test runs, it was found that, as expected, the most accurate GPS results could be captured with the U-Blox timer set to dynamic rather than stationary. Following completion of the tests the output data was checked to determine any timing inconsistencies between the Pi2X devices. Any discrepancies were corrected with post-processing.

Two series of tests were carried out. One was performed around the University of Nottingham Jubilee Campus and tested signal strength by distance, and foliage and building disruption. The second series of tests were performed in Wollaton Park, Nottingham, and tested signal strength by distance, and disruption due to foliage and hilly terrain.

3.3.5 DSRC – Jubilee Campus Test Results

Figure 3.15 shows the test route which was designed to incorporate the factors of distance, foliage and buildings between DSRC transmitter and receivers. The route was walked in an anti-clockwise direction with the second lap encountering denser foliage compared to the first lap. The Pi2X transmitter was slowly walked from 'X' following the route outline around the lake and buildings. Both the stationary receiver and mobile transmitter and associated equipment were monitored throughout the test to ensure continuous signal output.

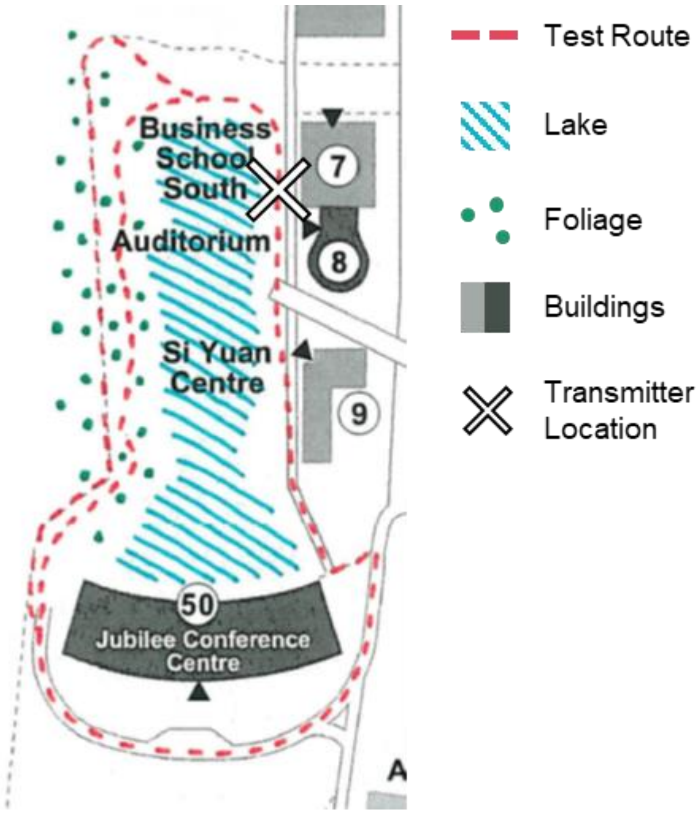


Figure 3.15 DSRC Jubilee Campus test route

The GPS accuracies from this test were consistent and accurate compared with the previous test runs, therefore it was assumed that the DSRC results could be reliably assessed with any fluctuations identified being assumed to be dependent on location, movement, and physical phenomena.

Figure 3.16 shows the results of the experiment and highlights the regions on which the following analysis was based.

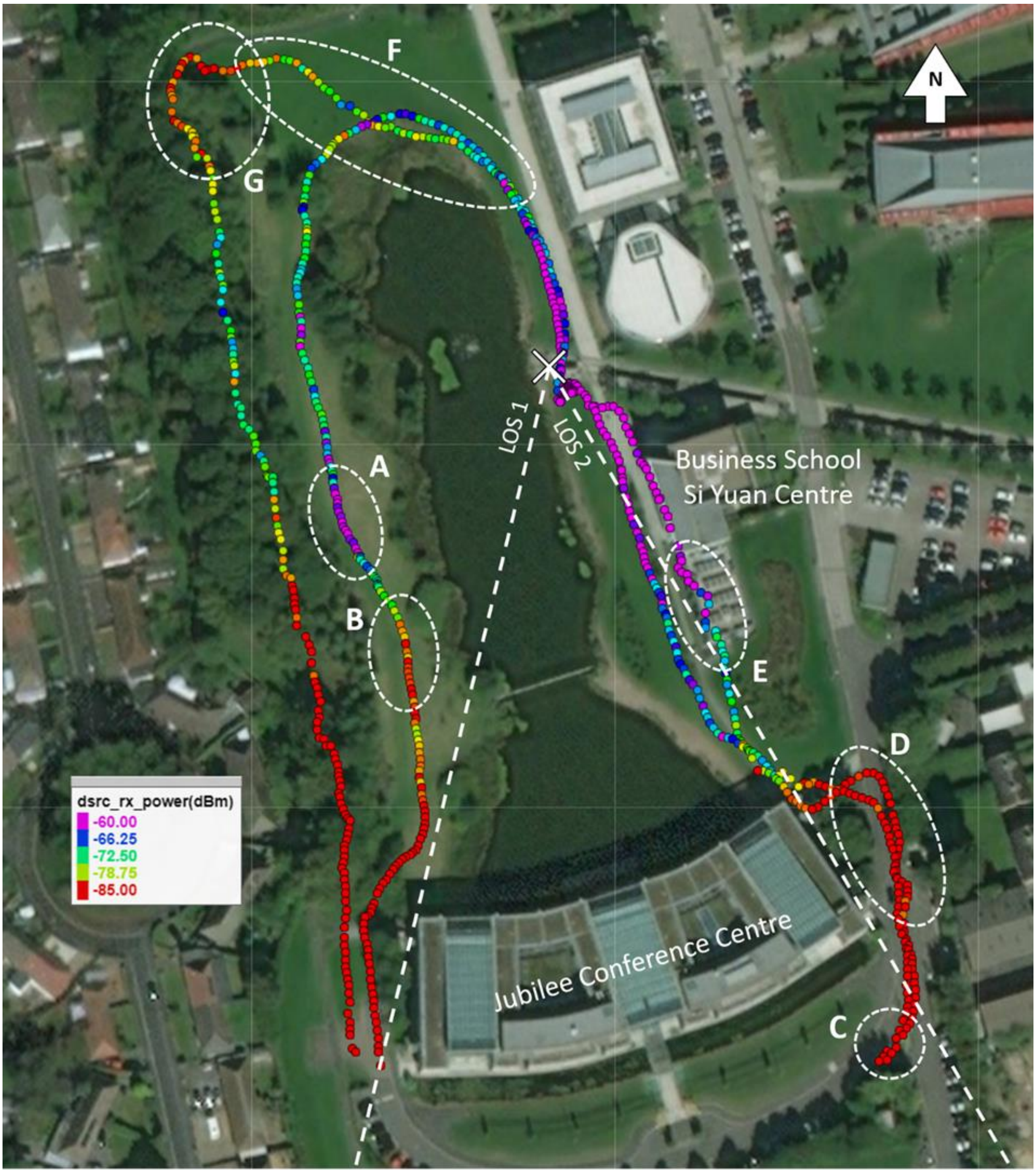


Figure 3.16 DSRC Jubilee Campus test results and analysis areas

A. Across the lake the DSRC signal becomes as strong as it was initially by the receiver at 'X'. This is because at 'A' there is a direct LOS for a sustained period. Previously, from the northern-most point of the lake the signal begins to fluctuate as varying densities of foliage are encountered.

B. Having been strong at 'A', the DSRC signal quickly becomes very weak at 'B' and from here fails to recover before the Jubilee Conference Centre. A large bush blocks the LOS between 'X' and 'B' which is the cause of this initial reduction in signal quality. Small gaps in the foliage can be assumed to be the cause of the slight fluctuation in signal strength after 'B'.

'LOS 1' is the line-of-sight from 'X' to the north-west corner of the Jubilee Conference Centre. This is a clear cut-off point for the DSRC signal suggesting that the signal relies on direct LOS.

C. However, 'C' shows the signal, although weak, returning despite being to the west of 'LOS 2'. 'LOS 2' demonstrates the locations of the corners of both the Business School and the Jubilee Conference Centre. According to 'LOS 2' the data points highlighted by 'C' are behind the Jubilee Conference Centre and assuming data cannot be received beyond LOS these data points should not exist.

D. The points highlighted by 'D' are behind the Business School and therefore not in LOS from 'X' either. Despite this, there is still communication between the roving transmitter Pi2X and the base receiver at 'X'. Both 'C' and 'D' highlight points that are out of LOS and conflict with the distinct cut off of DSRC signal west of the Jubilee Conference Centre.

   However, the nature of the signal could mean that points near to 'LOS 2' (which is a direct LOS from 'X' meaning that the points on the line 'LOS 2' can be seen from 'X') can be picked up.

E. These points show some error in the GPS positioning of the Pi2X device. Some of these points are shown to be inside the Business School, whereas the Pi2X device was walked around the school. The zigzag nature of these points is also indicative of poor GPS positioning. This was likely to be caused by the Pi2X device getting too close to the building, meaning that the sight line would have been partially covered by the building thereby restricting the GPS performance.

   When returning to 'X' DSRC signal becomes strong again as expected due to the assumed relationship between signal strength and distance between devices. The distance factor is important to consider across these experiments as it is another factor that affects DSRC signal strength. For instance, on Lap 2, the Pi2X is taken further west from the first route into some denser foliage (see G). Whilst denser foliage should result in weaker signals, the increased distance on the second lap is also a causal factor of this reduced strength.

F. This area highlights fluctuating strengths that are not particularly gradual with distance as would be expected. There is no foliage between 'X' and 'F' and compared with the DSRC strengths south of 'X' on approach (which are a similar distance from 'X') the points in 'F' to the north of 'X' are weaker than expected. This could be due to the person walking accidentally blocking the DSRC signal with their body.

G. The points in this area suggest the dense foliage between 'G' and 'X' in this corner of the route are affecting the DSRC signal strength as would be predicted.

   On the second lap the Pi2X device was taken through some trees along a paved footpath that is topographically lower than lap 1. The DSRC signals here fluctuate similarly to lap 1 but are generally weaker. This is mainly due to the denser foliage, but topology and distance from 'X' can also be considered as causal factors.

3.3.6 DSRC – Wollaton Park Test Results

The method for the Wollaton Park DSRC tests was similar to the Jubilee Campus tests, except for the location, routes and surrounding environment. The previous Jubilee test highlighted the potential effects of distance, terrain and topology on DSRC signal strength. The Wollaton Park tests were conducted to assess each of these factors individually. Therefore, three routes were plotted to test topology, foliage and distance effects separately.

Figure 3.17 shows the locations of the three tests with 'A' and 'B' representing the start and end positions of the tests respectively and 'D', 'F' and 'T' denoting whether the test is the distance, foliage or topology test.

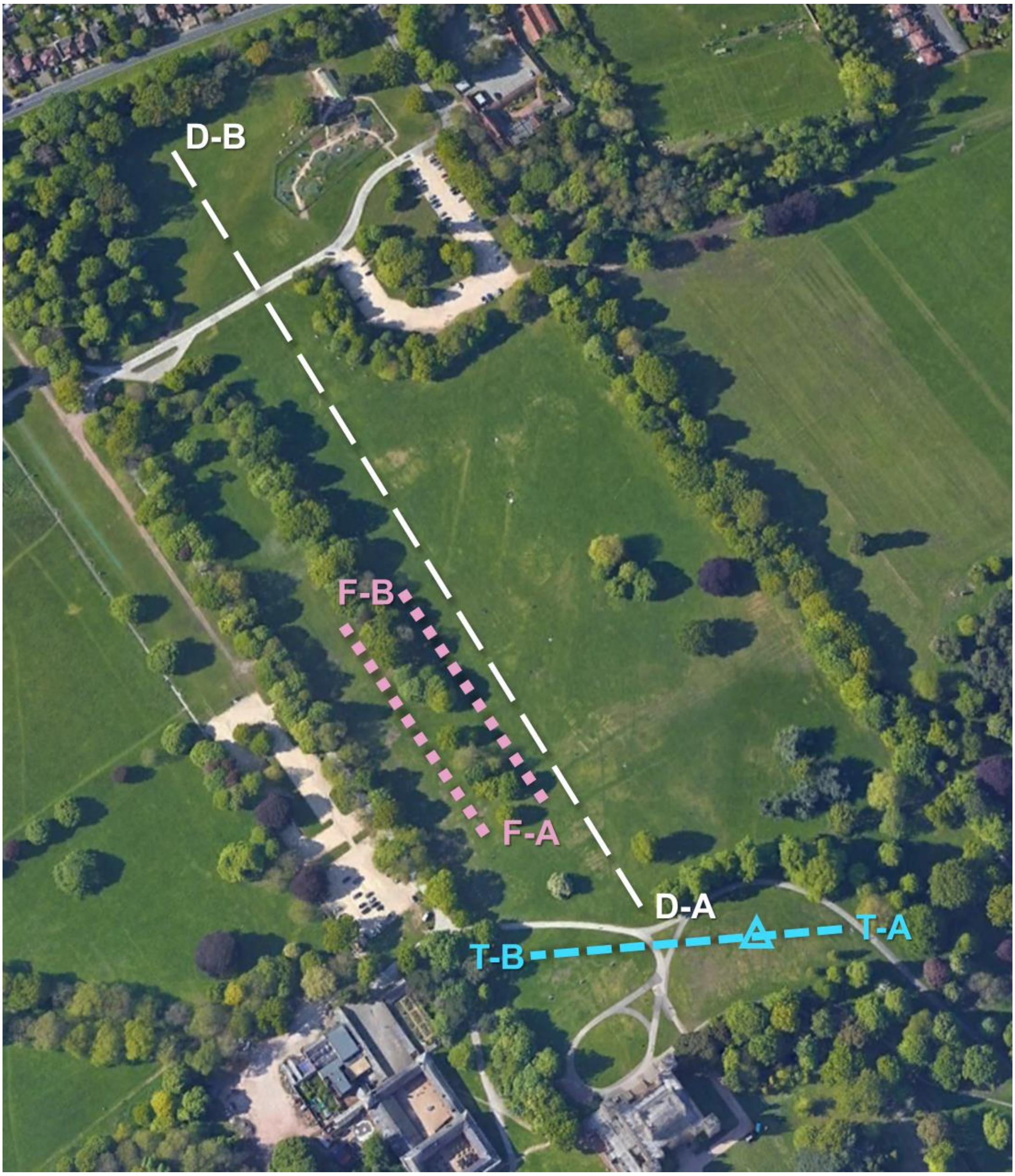


Figure 3.17 Wollaton Park DSRC tests

The distance test was conducted between points D-A and D-B in Figure 3.17. There was always a direct LOS between both these points. The receiver at D-A was topologically above the transmitter which was walked downhill towards D-B. This distance test was conducted to determine the influence of distance from the transmitter on signal quality. The distance test results were used to normalise the results from the topology test, where distance played a significant role in signal quality. Using SPSS, the distance test data was plotted revealing that the DSRC signal strength results were normally distributed which enabled correlation and regression statistical analyses to be performed. The analysis found a strong negative relationship between DSRC signal strength and distance between modules. Beyond 100m this was found to be a linear relationship (Figure 3.18). However, it was the quadratic equation that was found to be the most appropriate to use to normalise the DSRC distance effects, rather than a linear or cubic equation. Each equation was computed by SPSS based on a best-fit method. This equation was then normalised using SPSS also. Figure 3.18 and Table 3.3 show the results of the normalisation analysis, with the mean y-value of the normalised results required to be approximately equal to 0, with a linear gradient of 0. In this case, the x-value is the distance between modules and the y-value the DSRC signal strength.

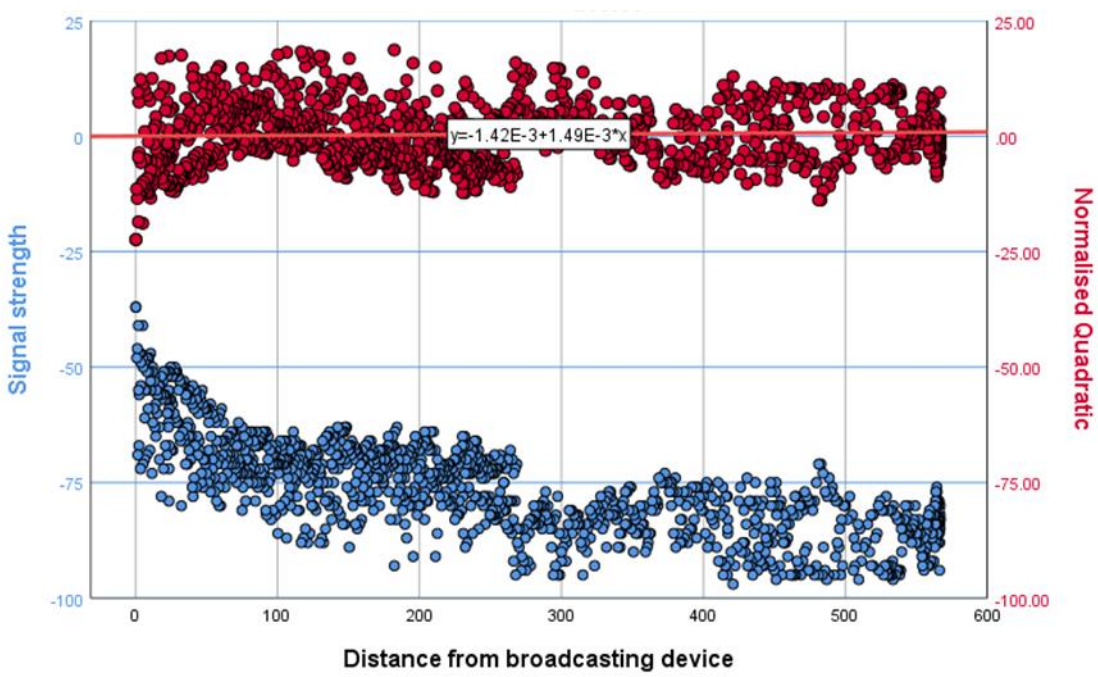


Figure 3.18 DSRC Distance test results and normalised quadratic

The foliage test was conducted between points F-A and F-B in Figure 3.17. In this case, both the Pi2X transmitter and receivers travelled together in parallel, starting off within direct LOS but then passing either side of an avenue of trees which intermittently disrupted LOS between the modules. This was done to ensure as little distance variations between the modules during the test as possible. The signal quality during the test dropped intermittently as LOS was lost due to tree obstruction. However, the signal quality was regained quickly after the drops and the signal was never completely lost.

Table 3.3 Normalised features of DSRC distance-relationship equations

Type	Normalised Linear Gradient	Normalised Mean y-value
Linear	- 0.00400	- 1.04
Quadratic	+ 0.00149	0.37
Cubic	- 0.00222	- 0.53

The topology test was conducted between points T-A and T-B in Figure 3.17 with the Δ symbolising the highest topological point on the route. Due to this highest point, T-A and T-B are not within LOS of each other. When compared to the distance test over 500m, the topology test that was only 200m experienced decreased signal quality at a more rapid rate suggesting an influence from the obstruction of terrain in addition to distance. The normalisation of the quadratic representing the distance-varied DSRC signal strength data above allows the analysis of topology effects on signal strength by removing the effects due to distance. Due to the topology test only reaching a maximum distance of 213m, points from the distance test over 250m were removed to determine the relationship of points within proximity to the transmitter similar to the topology test. This resulted in minimal changes to the relationship although does show a slightly reduced correlation. In this topology test, LOS was lost at approximately 80 metres. Applying the normalised equation revealed Figure 3.19, in which the region between 50 and 80 metres can be seen to change. This shows that in this test, LOS loss due to topology has an approximately 20 dBm effect on signal strength. From 100m there is little change, indicating that the normalisation equation has worked as after LOS is lost, distance is the remining DSRC signal strength factor.

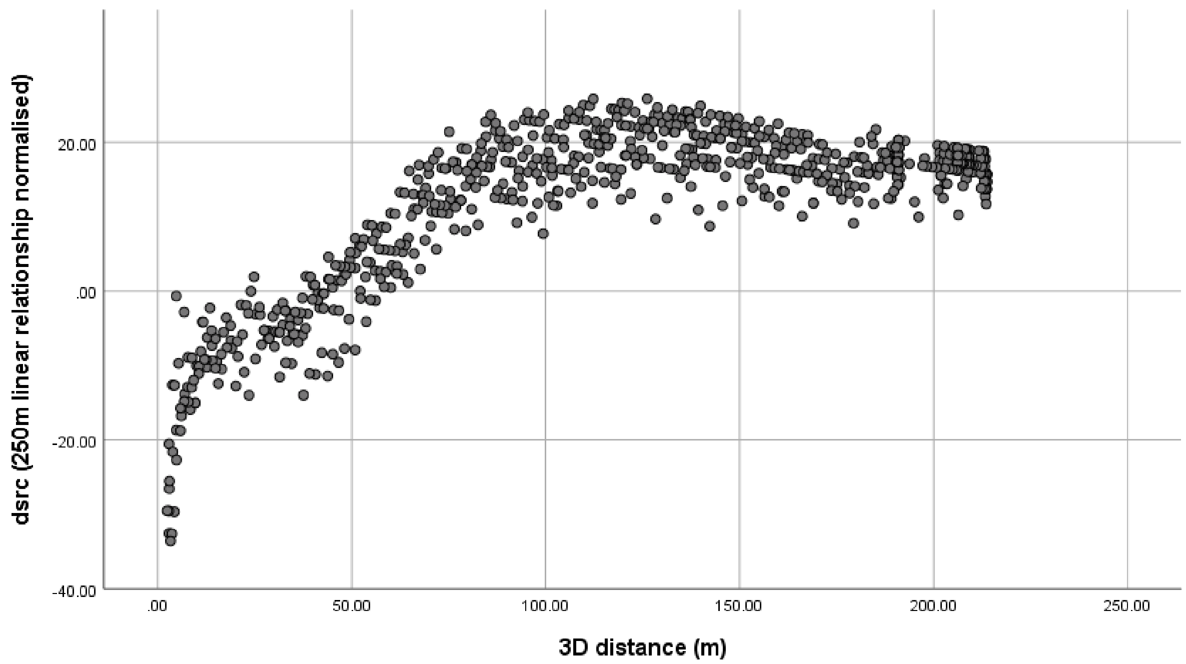


Figure 3.19 Normalised topology DSRC test results

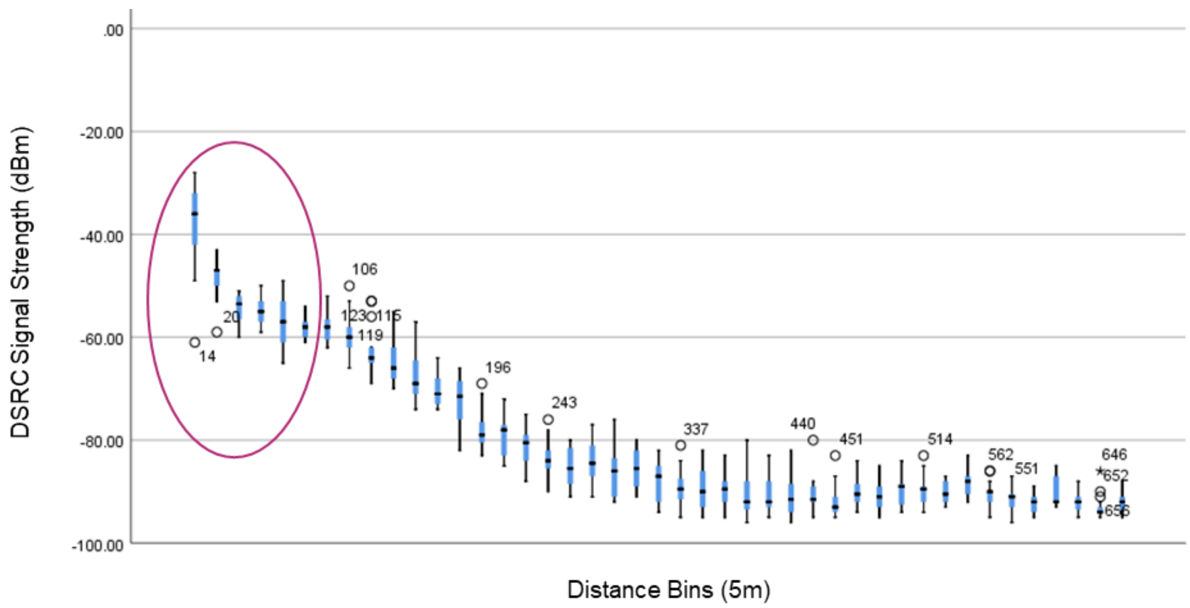
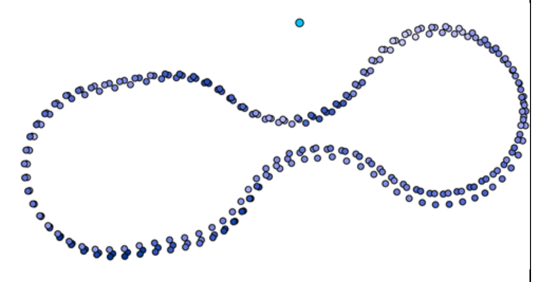
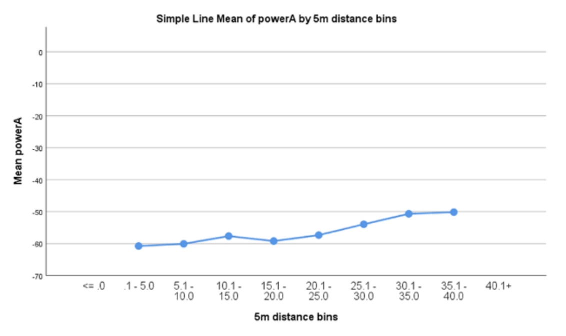
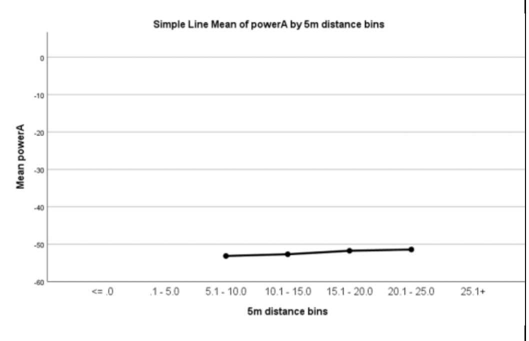
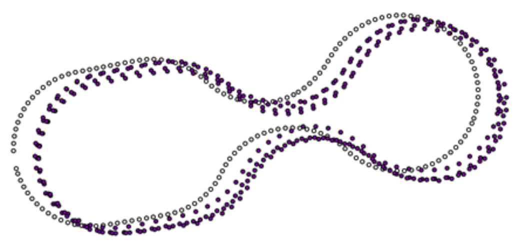
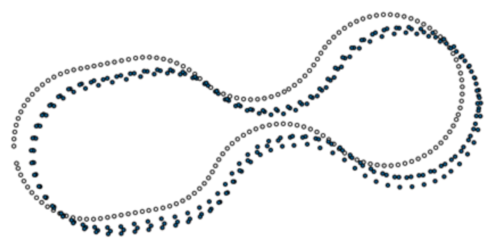


Figure 3.20 Boxplots of DSRC signal in five metre distance bins

Examining the results from the first 50 metres of the topology test in more detail showed large variations in signal strength. Figure 3.20 shows this in grouped five metre distance bins in which signal strength results are expected to be similar, but for the first 30 metres this is not the case.

Table 3.4 Summary of NGI roof track DSRC results

<table>
<tr><th></th><th>Test 1</th><th>Test 2</th></tr>
<tr><td>Transmitter position and signal strength</td><td></td><td></td></tr>
<tr><td>Signal strength description</td><td>The transmitter was positioned at the blue dot east of the track providing a maximum distance of 36m. The dark blue positions show the greatest signal strength. Generally, it appears that the strongest signal is at the furthest distance from the transmitter. This is also confirmed by the 5 metre bin graph below.</td><td>The transmitter was positioned north of the track in Test 2. A less obvious trend of signal strength with distance can be seen here. However, the 5 metre bin graph below confirms that in this test, signal strength increased with distance also. The maximum distance in Test 2 was 21m.</td></tr>
<tr><td>Signal strength (5m bins)</td><td>
</td><td>
</td></tr>
<tr><td>GNSS Position</td><td></td><td></td></tr>
<tr><td>Position description</td><td>Whilst the positioning of the receiver was relatively precise, the accuracy was generally off by 2m to the east. The device would benefit from a correction service to correct for this error.</td><td>The positioning of the receiver in Test 2 was more precise than Test 1 but less accurate with 2.5m error to the south east.</td></tr>
</table>

To explore these varied short-range results in more detail, an additional test was set up using the NGI test track. For this test, as well as recording DSRC signal strength, packet error rate was also recorded as an additional indicator of signal quality. However, in the NGI roof tests the packet error rate was <0.05% and therefore negligible showing that in these short-range tests the packet error rate was not an influential factor on the abnormal signal patterns seen in the Wollaton Park tests. The NGI test track features a precise miniature railway for satellite positioning testing and calibration. In this case, it is used as a precise route along which DSRC signal strength can be tested to up to 36 metres distance. The DSRC transmitter was stationary, and the receiver attached to the moving train. Table 3.4 summarises the tests and describes the results.

These test results revealed that at short-range DSRC signal is weaker when the DSRC modules are closer together and that some distance is needed between the transmitter and receiver in order to achieve the greatest signal strength.

3.4 Investigative Discussion

In this chapter a number of technological and infrastructural challenges facing the implementation of CAEVs on rural roads were identified. Namely, these challenges are of satellite positioning quality and availability, the readability of roads and their maintenance, 4G signal strength and reliability and DSRC V2X communications in rural environments.

Combining road definitions, environment categories, GNSS positioning data and route video footage, the relationships between GNSS and sensor positioning techniques across a variety of road environments were assessed and their associated and combined challenges identified. Unlike environment density, road mark density (the amount of road markings on a road) has no effect on the quality of GNSS NRTK positioning. Road markings can, however, be used to assist positioning via sensors and their extracted locations can help to relatively correct the trajectory of the vehicle. It is important to compare both environment density and road marking density as there are relationships that can be assessed. For example, the results conclude that densely covered environments have the highest proportions of fix loss. Typically, busy urban roads have heavy density road markings to help control traffic. At the same time, these areas are heavily built-up and therefore are vulnerable to poor satellite connectivity. In these cases, heavy road markings are proportional to dense building environments. The densest urban environments therefore house roads that are still readable and highly navigable if relative sensor technologies are used, despite lacking accurate GNSS positioning capabilities. It is mostly urban areas with these dense features, but they can also exist in rural areas. However, the key finding in Figure 3.11 is that 32% of unreadable rural roads lost fix. With no markings for CAEV sensors to read and no guidance from GNSS positioning, the vehicle would be essentially blind for that 32% of travel time on these unreadable roads.

These results support findings from the literature that the procedures for the maintenance of markings need to be improved (Gowling WLG, 2018). Additionally, road signs need to be checked for cleanliness and clarity more frequently than at present. However, road maintenance periods can create issues for CAEVs. The re-laying or re-marking of roads, as well as the replacement of road signs, takes time. During maintenance periods road markings can disappear completely, and roads can become temporarily unreadable. An example is shown in Figure 3.21. For CAEVs, the process of changing and maintaining road environments presents a challenge.

Figure 3.21 "No Road Markings" sign on a recently re-surfaced road

The technical requirement for a good road marking is defined by the European Road Federation (EuroRAP, 2011, King, 2013). During the 2018 trial, and by reviewing video footage and photographic evidence taken throughout the study, it was clear that the road markings along the test route were inconsistent; suggesting that they do not all meet the requirements set by the definition of a good readable road marking. This lack of consistency regarding road marking density and road marking quality, presents a challenge to the implementation of CAEVs across rural areas in the UK. A survey by the British Standards Institution (BSI) found that '*road and road-side physical infrastructure*' was one of the most important areas in which developing consistent standards would be useful in supporting the development of the UK CAEV industry (Fleming et al., 2017b). The results from this study support the findings from the BSI and suggest that road and road-side physical infrastructure standards would not only be useful, but required, to ensure the safe deployment of CAEVs across the UK, especially on rural roads.

This investigation has found that satellite positioning quality is primarily governed by the LOS connection between the satellite and CAEV GNSS receiver, and that densely covered environments are the most likely to result in the loss of fix and poor positioning quality. Whilst urban environments are more densely covered, the average amount of fix loss on rural and urban roads are similar; 26.4% and 25.3% respectively. One reason for this similarity is the shape and nature of trees compared to buildings. Tree cover tends to have a greater impact on fix loss due to the overarching nature of trees across and above a road. With buildings, there is usually sky visible directly above. The current availability of NRTK is not yet good enough for continuous tracking in densely, or even lightly, covered environments. This report's conclusion supports that of Aponte who finds that, although NRTK successfully provides safe positioning accuracies, its lack of availability means that it can only be used uninterrupted in clear open sky environments with very few obstacles(Aponte et al., 2014).

This lack of continuous accuracy is a major challenge facing CAEVs on rural roads. LOS obscuring trees prevent safe positioning accuracies from being achieved, and whilst the same problem is present in urban areas, trees appear to have a more unpredictable impact than buildings. The LOS issue is being investigated by current

UK urban CAV tests, but investigation into the impact of rural tree cover is also required.

With over a quarter of rural road time losing fix level GNSS positioning accuracy and 17.9% of rural roads unreadable, effective communications are critical to rural CAEV implementation. However, based on the literature and investigations in this chapter, rural cellular coverage is lacking, suggesting that presently it cannot be safe for CAEVs to travel on rural roads. The well-documented discrepancy in cellular coverage between rural and urban areas in the UK is supported by the findings in this investigation. The results from the 4G cellular tests highlight that rural roads suffer from variable and unreliable mobile connectivity. Due to the poor cellular coverage across the country, some vehicle manufactures say that the UK market is not a viable one for launching new CAEV functions. This gives the UK an economic incentive to develop the connectivity of both rural and urban UK roads. Steps are being taken to do this, including installing fibre-optic networks on large sections of UK motorways(Anonymous, 2017a). However, the 79% of UK traffic not carried by motorways will have to rely on cellular 2G, 3G, and 4G which has been shown to be lacking.

Many of the positioning challenges in rural areas have the potential to be solved to some extent through V2X technologies. These investigations have found that DSRC performance is capable of delivering connectivity between rural CAEVs. However, there are correlations between dense foliage and reduced DSRC signal strength. Buildings greatly impact the quality of signal strength, removing it entirely in some cases, which is likely to be of greater concern in urban areas. Further, distance, weather and topology are all factors to consider regarding DSRC signal strength. In terms of V2X communications there is still work to be done to determine the specific reasons behind DSRC signal fluctuations, which could be mitigated using higher quality GNSS positioning and accurate mapping. Achieving these will allow the exact physical obstacles that affect DSRC signal to be identified and then their condition, type and physical features can be assessed.

Based on the findings of this chapter, CAEV challenges are wide and varied, although steps are being taken to improve CAEV's ability to deal with rural roads and scenarios. However, primarily both UK cellular coverage and road marking standards and quality need to be improved and investment in infrastructure and technologies suited to specifically rural areas is needed (Bosworth et al., 2020). This report therefore supports the conclusions of Fleming, who suggests that there is a great need to upgrade existing physical and digital infrastructure for the implementation of CAEVs as existing infrastructure is currently incompatible with the CAEV technology being developed(Fleming et al., 2017a).

3.5 Non-Technological Challenges

Whilst the bulk of this chapter explores technological and infrastructural challenges to rural CAEV implementation there are other non-physical challenges. In the interest of completeness, the following section summarises some of the most cited non-technological CAEV implementation challenges. Whilst not the focus of this thesis, as CAEV implementation is a complex and multi-disciplinary problem, it is important to have an awareness of these societal, economic and political and institutional challenges.

Whether and to what extent potential users would trust an autonomous road vehicle is one of the most researched human factors challenges regarding CAEV implementation. There are many factors which contribute to the level of acceptance a user might have regarding using a CAEV (Filip et al., 2016, Schoettle and Sivak, 2014, KPMG, 2019). These can include the complexity of integrated human and automated driving (Brown, 2017, Carsten and Martens, 2019, Rahman et al., 2018); the historic and perceived capabilities of CAEV technology (Filip et al., 2016) including positioning and navigation (Filip et al., 2017); statistical proof that CAEVs are safe (Ford, 2019); individual and societal ethical perspectives and responsibility (Marcus, 2016, Sparrow and Howard, 2017); cyber-security concerns (BSI, 2018); and even an individual's willingness to simply ride-share with another person (Midlands Connect, 2020a). Whilst the benefits of CAEVs for road users are increasingly widely acknowledged, surveys have returned mixed public opinion (Murphy et al., 2017, Schoettle and Sivak, 2014). Public trust can be achieved through rigorous testing and certification; the proven effectiveness of a CAEVs situation awareness; and continual transparency of accuracy, reliability, and sensing quality (Filip et al., 2017). However, even with these assurances, people can be unwilling to trust technology with their lives.

Further to trust and acceptance, Zhang (2019) produces a detailed investigation into the social factors influencing CAEV adoption potential. These include personal and societal demographic information, education, employment, household structure and income, vehicle ownership, transport use, trip purpose and frequency and location of work and residence (Zhang, 2019). Cultural and educational issues relating to people’s ability to use the internet, and as a consequence misunderstand CAEV technologies and services such as ride-hailing can also be a barrier (Midlands Connect, 2020a), whilst basic access to the internet is itself an issue.

Whilst investment in CAEVs is growing, specific investment in rural CAEV trials and implementation is lacking despite the complexity of rural environments (Bosworth et al., 2020, Midlands Connect, 2020a) and the findings of this thesis. There must also be consideration regarding the cost to the user, both to implement and use CAEV technologies (Hensher et al., 2020, Lakatos et al., 2020), although it is predicted that CAEV implementation will dramatically reduce user cost (Docherty et al., 2018).

The initial costs of buying and adopting CAEVs however are expected to be high, making up front cost a significant barrier (Fagnant, 2014, Murphy et al., 2017) as they will require top of the range technologies to function (Cui et al., 2017) amongst other factors. Further, it is commonly perceived that CAEVs will result in unemployment due to automation (Bloomberg, 2017, Evas, 2018). However, there are ongoing studies as to whether this, or in fact the opposite (Automotive Council, 2011, European Commission, 2019b, McCarthy and O'Keeffe, 2019), will be the case (Murphy et al., 2017).

Another challenge facing CAEV implementation is the political and institutional will and capacity to implement change. Whilst better planning, governance and regulation using data science and analytics are still needed (Bosworth et al., 2020), there is interest in progressing CAEV implementation as outlined in government technology and transport plans (BEIS, 2017, DfT, 2021c). Further, the CCAV continues to promote and fund CAEV projects (CCAV, 2020, CCAV, 2019); however, more action is needed surrounding rural CAEV implementation (Bosworth et al., 2020, Murphy et al., 2017). The political and institutional will to implement rural CAEVs are discussed in greater detail in Chapter 4 which directly investigates the challenges facing those in the transport planning industry.

3.6 Conclusion

Serious consideration must be given to the challenge of establishing the infrastructure that is needed to support rural CAEV implementation. The findings of this chapter suggest that rural road infrastructure needs to develop to meet the standards of current urban roads. Ultimately the UK is not yet ready for full scale implementation of Level 3, 4 and 5 CAEV technology. Whilst GNSS positioning consistency and cellular coverage continue to be addressed, basic road infrastructure, particularly road markings, is inconsistent if not lacking altogether. There needs to be more emphasis on improving basic infrastructure in rural areas, otherwise it is only the urban populations that will be able to benefit from CAEV technology.

With over a quarter of rural road time losing fix level accuracy, the addition of poor cellular coverage means that it is difficult to justify safe rural CAEV implementation where 19% of rural are also unreadable. The infrastructure challenges are clear: UK cellular coverage and road marking standards, quality and consistency need to be improved to ensure that CAEVs have consistent and safe environments in which to operate. This conclusion therefore supports that of Fleming, who suggests a need to upgrade currently incompatible physical and digital infrastructure for the implementation of CAEVs (Fleming et al., 2017b), but particularly highlights a greater need for this intervention on rural roads.

4 RURAL TRANSPORT PLANNING AND CAEVS

In Chapter 3 the challenges facing CAEV implementation in rural areas were discussed and both infrastructural and technological issues facing the ability of CAEVs to serve their safety and efficiency purposes were identified. Whilst the infrastructural areas that need improvement in order to deliver CAEVs and their benefits to rural areas were set out, the practicality of such improvements were not considered. Those responsible for practically implementing the infrastructural and technological changes needed to support rural CAEV adoption are rural transport planners.

Transport planners are built-environment professionals who manage and improve transport systems by designing and developing policies, plans and strategies considering economic, social and environmental factors. Transport planners should understand current and future transport systems that specifically cater for the communities which they serve. It is important that transport planners engage with and understand their communities in order to deliver and promote sustainable transport solutions. For the purposes of this thesis, a rural transport planner works to manage and improve specifically rural transport systems for rural road users and rural communities. Whilst this research will refer to rural transport planners, it recognises that transport planning is a diverse discipline and that transport planners may work in a variety of roles that may not be specifically rural, including urban transport planning.

For CAEV implementation to occur, rural transport planners need to consider the infrastructural requirements of CAEVs, many, but not all, of which were discussed in Chapter 3. These include the planning of physical infrastructures for CAEVs such as readable road signs and markings, good quality and well-maintained road surfaces and electric charging networks. CAEV supporting infrastructure further includes digital infrastructures such as wireless communication networks. Transport services, including public transport, must also be considered by transport planners, as well as technological implementation schemes to increase awareness of CAEVs and related technologies. These schemes are relevant to all stakeholders in rural transport development, including professionals such as planners and engineers, as well as the public.

It is transport planning professionals that should possess the knowledge needed to identify the practicalities of new transport system implementation. To do this, they must understand existing transport systems and their challenges. They are then able to identify areas in need of change and take steps to implement appropriate methodologies to generate that change.

4.1 Hypothesis

It has been unclear to what extent the transport planning profession is aware of, understands the technology behind, and believes in the specifically rural benefits of CAEVs and their technologies. Therefore, to support the research objectives of this thesis, this chapter addresses the following research questions:

A. To what extent is the implementation of rural CAEV technology currently a priority for transport planning professionals?

B. To what extent do rural transport planners believe that CAEVs are an important factor in the consideration of future sustainable transport solutions?

C. To what extent do rural transport planners understand CAEV technologies and their infrastructural requirements?

These questions have resulted in the development of an elicitation methodology. The surveys constructed collect a broad sample of professional transport planner's thoughts towards the topic of rural CAEV implementation, whilst complimentary interviews took an in depth look at the practicalities of rural CAEV implementation with the leaders of transport planning groups. The findings in this chapter link the findings of Chapter 3, highlighting the lack of infrastructure capacity to support rural CAEVs, with the identified need to develop the CAEV Rural Transport Index

(CARTI) described in Chapters 5. To do this, the transport planning professionals shared their thoughts on the usefulness and effectiveness of the proposed CARTI, which were used for the index's development, application and evaluation.

The hypothesis driving the research in this chapter is that a lack of rural implementation research and trials means that rural transport planners are likely to be ill-informed and uncertain of both the potential of CAEVs and their implementation requirements. Given this hypothesis, the CARTI solution, which has been designed to aid rural transport planners in understanding the requirements and decision-making regarding rural CAEV implementation, was proposed. This hypothesis was tested using the following methodology that describes the process of engaging with transport planning professionals to establish their perspectives on the issue of rural CAEV implementation and the proposed CARTI solution.

4.2 Elicitation Methodology

To start to understand rural transport planner's perceptions of CAEVs and their rural implementation potential, an elicitation method was required to collect the thoughts and opinions of these professionals. However, qualitative elicitation is more common among social science research disciplines rather than engineering disciplines. Elicitation methods in non-social-based studies, such as interviews, are often used to collect data that cannot be obtained quantitively and where goals are of a qualitative nature (Bıyık, 2019)(Hove and Anda, 2005). Therefore, to determine the most suitable type of elicitation for this research project, a methodology presented by Egas (2015) was used.

The following tables apply the requirements of this research to Egas' elicitation selection methodology by ranking different attributes (Table 4.1), scoring different elicitation methods according to their attributes (Table 4.2), and then assessing the highest four scoring methods to compare and select the most appropriate method for this study (Table 4.3) (Egas, 2015).

Table 4.1 Elicitation study requirements and attribute rankings (based on Egas, 2015: page 19)

Attribute		Description	Reasoning	Rank
A	Experience with elicitation methods	This attribute is related to the number of elicitation study's the elicitor has already carried out.	The elicitor has previously been involved in two projects where written surveys formed the basis of data collection, albeit in a data analysis capacity.	Low
B	People per session	This attribute relates to the number of people required per elicitation session.	Individual viewpoints on the state of the rural planning industry were required; COVID-19 restrictions meant that group gatherings were restricted.	Limited
C	Consensus among informants	This attribute assesses the need for a consensus among participants to clarify requirements prior to the elicitation method taking place.	Participants did not need to agree on the method of elicitation as a group; prior to participation an individual must consent to the elicitation method; for the elicitation to take place participants must have read and approved data protection guidance; if a participant disagreed with the elicitation method, they would have been unable to take part.	Medium
D	Articulability	This attribute relates to the participants skill at explaining their knowledge and the impact this will have on the elicitation.	The target participants were transport planning professionals who will typically have a strong grasp of their field; the elicitation required respondents to discuss CAEVs of which their knowledge is unknown.	Medium
E	Availability of time	This attribute assesses the impact of the amount of time the elicitor and participants have available to complete the elicitation.	The elicitor's time to complete a significant number of elicitations was a few months; a large amount of time would be required from the elicitor to complete each elicitation and then to assess the results; participants were likely busy professionals with the time needed to participate impacting their professional lives.	High
F	Location and accessibility	This attribute reviews the impact of elicitation location on the elicitor and participants.	As described in B, elicitations were conducted individually; COVID-19 restrictions and convenience dictated that only online elicitation will take place.	Low
G	Information available	This fundamental attribute assesses the amount of information available that the elicitation is attempting to extract.	The elicitation method attempted to extract large amounts of knowledge that already exists from the experiences of the participants who are professionals and experts in transport planning, and related, fields.	High

Table 4.2 Elicitation evaluation based on attribute ranks (based on Egas, 2015: page 20)

Method	A	B	C	D	E	F	G	Score
Attribute Ranks	*Low*	*Limited*	*Medium*	*Medium*	*High*	*Low*	*High*	*Total*
Interview (unstructured)	L	L	L	M	M	M	H	**4**
Interview (structured)	L	L	L	M	M	M	H	**4**
Task analysis	M	M	M	L	M	H	H	2
Card Sorting	M	M	M	M	M	M	H	3
Surveys	L	H	M	L	H	L	H	**5**
Protocol analysis	L	L	M	M	M	M	L	**4**
Repertory grid	H	M	H	H	M	M	L	0
Brainstorm	L	M	H	H	M	M	M	1
Nominal Group Technique	M	M	H	H	M	M	M	0
Delphi	H	M	H	H	M	M	M	0
Observation	M	M	M	L	H	H	M	2
Prototyping	L	M	H	M	H	M	L	3
Focus Groups	M	M	H	H	M	M	M	0
JAD workshop	H	M	H	H	M	M	M	0
Scenario analysis	M	M	M	L	H	M	L	2

Based on the assessment in Table 4.3, protocol analysis was ruled out. Protocol analysis focuses on problem solving for a specific solution and was therefore found to be irrelevant. This type of elicitation method would be more suitable for a hypothetical research stage where, for example, a specific rural transport planning problem was encountered. Both surveys and interviews (unstructured and structured) however, were appropriate elicitation methods to research the perspectives of transport planners.

Table 4.3 Elicitation method assessment (extracted from Egas, 2015: page 21)

Method	Score	Applicability	Advantage	Disadvantage	Conclusion
Survey	5	Reach a big audience	Anonymous	Dependant on the participants for submission	Get a lot of information of people in different locations
Interview (unstructured)	4	Applicable in most cases	Easy for a lot of people; quick	Don't know if you ask the right questions	Could be used as starting point
Interview (structured)	4	Applicable in most cases	Quick; same questions in multiple sessions	Little bit of preparation time	Could be used as starting point
Protocol analysis	4	Procedures, problem-solving strategy	Solution focus	High dependence on the knowledge of the informant	To deep dive to a specific requirement

Surveys have the potential to gather a lot of information from a large number of people. This allows participants who may not have the time to commit to an interview to instead work on a survey intermittently, or over a shorter period of time. The greatest risk of a survey, however, is a lack of responses. This could be mitigated through direct communication with a participant inviting them to complete a survey, or contacting an administrator, or someone with influence, who could circulate the survey to a group of potential participants.

Interviews guarantee responses as long as the participant agrees to the interview in the first place. However, due to participant time constraints, responses may be limited, and details omitted, which have may otherwise have been collected via a survey with no time constraints. There is also a balance to be found between asking short and long questions to make best use of the time available. Simple and short questions would be needed to assess fundamental research questions. Long, in-depth questions could potentially lead to valuable insights, but at the same time there is a danger of uncovering little of research interest. As the description in Table 4.3 also suggests, interviews can be good starting points and can be used to influence any surveys conducted at a later research stage.

4.2.1 Participant Sampling

The advantages and disadvantages of both survey and interview methods had the potential to impact the quality of this study. Therefore, both methods were presented to potential participants. Quantitative and short qualitative data were collected via an online survey to ensure the collection of the fundamental knowledge necessary for this research study. Complementary to this, interviews were carried out with specific professionals with known expertise to support, and scrutinise, the survey findings and the findings of this thesis, in high qualitative detail.

The target participants for elicitation were specifically transport planning professionals. However, due to the breadth and complexity of the research subject, other professionals with strong links to rural transport development and / or CAEV development and implementation were also targeted. Therefore, the nonprobability method of purposive sampling was used. This method is used across research industries to specifically target individuals with knowledge in a certain area so that the data collected is meaningful to the aims of the research (Battaglia, 2011, Guest et al., 2013, Trochim, 2021). Despite the associated bias of the method, purposive sampling is efficient in that the selected individuals are assumed to have knowledge of the research subject and any individuals with no knowledge of the subject are filtered out prior to the elicitation. However, selected individuals, although assumed to be knowledgeable, may not necessarily be reliable (Tongco, 2007).

To further filter non-knowledgeable and non-reliable participants, the participant information section of both survey and interview forms made clear to potential participants the types of respondents required for the study prior to elicitation. The preamble states that the individual was:

> *"…selected as a potential participant for this survey due to (their) knowledge and experience in transport planning and/or of connected and autonomous vehicles."*

Extract from Participant Information Sheet (Appendix B)

Participants must have read and signed this section and associated text as part of the consent proceedings required by the ethics guidelines behind this academic study (see Section 4.2.5). This acted as a secondary filter to individuals without the appropriate perceived background knowledge or experience who could then withdraw from the elicitation process.

For individuals accepting the terms of the study and confirming their consent to partake in the elicitation, a further third filter was put in place to ensure reliable and competent results were obtained. In the initial stages of both survey and interview elicitations two questions were asked of the individuals to gauge their knowledge, experience, and expertise of the subject matter.

"Who is your employer?"

"Briefly describe your job role."

Survey Questions 4 and 5 (Appendix B)

This filter was designed for the use of the elicitor in two capacities. The first was to understand the background and experience of the participant. It was then the elicitors prerogative to determine whether the participant has provided useful data for the purposes of the research, based on their background. The second was to gauge the level of experience, an indicator of data richness, of the participant to determine the meaningfulness of the data contributed. For example, this allowed the comparison of data provided by a newly graduated planner to that of a project manager with more years of experience and knowledge of the subject area. This filter could have also been used to derive expert sampling, a subset of purposive sampling where only experts in a field would be asked to participate in an elicitation (Trochim, 2021).

4.2.2 Question Development

The structure of questioning for each elicitation method required careful consideration. The structure was designed to maximise the usefulness of the data whilst reducing the time taken to complete the elicitation for each participant. By minimising the number and complexity of questions a higher response rate could be achieved (De Leeuw et al., 2008).

To ensure the data collected was useful, the questioning aimed to extract data that directly contributed to this research study and, more broadly, the aims of this thesis. As such, consideration of *why* each question was being asked was needed to determine *what* these questions should be asking. As both survey and interview elicitations acted to support one another, questions for both survey and interview were developed together. Once defined, the questions were then split to form question schedules for the survey and interviews separately, depending on the characteristics and scope of each question.

To begin constructing the question schedule, a list of topics and related questions was drafted relevant to the research aims (Blackstone, 2012). This list was transferred into a spreadsheet that split the questions according to their level of required detail. Questions requiring simple responses, such as qualitative, one-word or single sentence answers, were defined as potential survey and interview questions. Questions requiring more detailed answers, and those where there was potential for discussion, were defined as potential interview questions only. Questions were also assigned a suggested answer type; either being *open-ended*, *yes or no*, or requiring a *rating scale*. The spreadsheet also expanded on the simple questions to suggest ways in which a simple survey question could be developed into a more complex and detailed interview question. Finally, the reasoning behind why that question should be asked was recorded to ensure that each question was relevant to the research. This also provided a method to assess the potential importance and impact of a question. To simplify the spreadsheet into a clear question structure, the most important and relevant questions were identified and similar questions grouped (Blackstone, 2012).

4.2.3 Survey Methodology

The survey was developed to be used to collect the fundamental knowledge required to answer each of the research questions described earlier in this chapter, and to explore the research hypothesis, as a minimum. Following the development of the elicitation questions, survey-appropriate questions from the question spreadsheet were extracted and developed through consultation with the University of Nottingham Faculty of Engineering Ethics Committee and project supervisors. The final question schedule for the survey can be found in Appendix B.

The survey was created on Microsoft Forms, which made it possible to develop an interactive and simple survey with a mix of option, rating, and short and long text answer types. Following tests with other researchers and non-experts, the survey was determined to take an approximate average time of ten minutes. The ease of use and short time window required to complete the survey helped to ensure a substantially different type of elicitation method was available to participants complementary to the interview method.

Whilst generic sampling has been discussed, survey-specific participants were selected in three stages. The primary aim of the interviews was to gather detailed information regarding specific areas of the research topic, but the survey acted as a broader elicitation method seeking participants with some, but varying degrees of, experience and knowledge of rural transport planning, development and CAEV implementation. Initially, interview targets that declined to partake in an interview were asked to complete the survey as an alternative. This yielded few responses. Secondly, interview participants were asked at the end of their interviews if they would be willing to share the survey with their professional networks. This yielded the majority of survey responses as it was able to reach previously unfamiliar networks. Finally, potential survey participants were sought more broadly. Selected groups and organisations with links to rural development and transport were contacted with requests to share the survey with their members. These groups were selected based on conversations with interview participants, supervisors, key contacts known by the researcher, and via internet search for relevant groups. These groups included but were not limited to the Transport Planning Society (TPS), Rural Services Network (RSN), Royal Institute of Navigation (RIN), International Transport Forum (ITF), and the Commonwealth Association of Planners (CAP).

In each case, the survey contained contextual and background information to improve the participants understanding of the nature of the questioning and research. Following the completion of the survey, each participant was invited to interview to discuss their responses in further detail. This provided an opportunity to uncover further potentially valuable and detailed insights.

4.2.4 Interview Methodology

The interview question schedule was developed in the same way as the survey question schedule and can be found in Appendix B.

Interviews can be resource demanding and time-consuming for both elicitor and participant. It was therefore important to create a comfortable interview environment which encouraged participants to share their experiences (Hove and Anda, 2005). Although the interviews for this study were technically-focused, rather than social-based, it was still important to create this sense of environment. This was made easier by adopting a semi-structured interview style where participants were free to veer away from the direct line of questioning and into their own areas of expertise where they would likely be more comfortable.

Semi-structured interviews are a commonly used qualitative method to understand participant perspectives on specified topics (Egas, 2015, Hove and Anda, 2005, Longhurst, 2009). Semi-structured interviews provide flexibility within a consistent framework to better understand the perceptions of participants (Santoso et al., 2011).

The interview questions were designed to begin relatively simply, remaining factual and specific to the participant’s knowledge, and then build up to more complex and potentially thought-provoking questions (Lupton, 2020, McNamara, 2006). The question schedule was ordered logically so as not to interrupt the flow of the participant. This encouraged early engagement and created a comfortable environment from which momentum was built throughout the interview. This enabled participants to engage with the more complex questions at the later stages.

The interview ended with the elicitor inviting the participant to ask questions of the interview and proposed research. This further contributed to the conversational style and provided the participant with a sense of control, providing them with an opportunity to add any additional impressions that they had (Lupton, 2020, McNamara, 2006). This was also of benefit to the elicitor, as ideas were contributed to the iterative improvement of the interviews and the research proposal itself.

The interviews were conducted using Microsoft Teams software and each interview was recorded with the permission of the participant. Whilst a transcription of the interview was provided automatically in Microsoft Teams, each interview was manually transcribed to reinforce the elicitor's understanding of the results (Blackstone, 2012). There was also the accuracy of Microsoft Teams' automatic transcription service to consider. Comparison with the elicitor's transcription was beneficial and helped to reduce transcription errors.

The potential interview participants were contacted directly via the networks established through the Transport, Mobility and Cities Research Group at the University of Nottingham. In this way, specific participants were targeted based on their known knowledge and expertise in fields related to this research, specifically the technology, human, and infrastructure aspects of CAEV implementation.

4.2.5 Consideration of Ethics and COVID-19

With any academic qualitive study involving human participants, ethics is a priority consideration. Ethical review and approval are requirements for such studies involving human participants and their data.

In preparation for this elicitation study, the elicitor had undertaken a comprehensive online Research Integrity course as outlined by the University of Nottingham Statement on Research Integrity (University of Nottingham, 2019). The elicitor had also reviewed the University of Nottingham Code of Research Conduct and Research Ethics which provides a comprehensive framework for good research conduct and research governance (University of Nottingham, 2020).

All participants in either survey or interview elicitation gave their informed consent for inclusion before participation. Through consultation with the project researchers and supervisors this study was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013), and the protocol was approved by the University of Nottingham Faculty of Engineering Ethics Committee following receipt of an Ethics Approval Form; Study Information Sheet including a summary of the interview and survey questions to be asked; a Participant Information Sheet to be reviewed by all participants prior to elicitation; and a Participant Consent Form to be signed by all participants prior to elicitation. These, and the Ethics Committee Reviewer Decision, can all be found in Appendix B.

As mentioned briefly in Table 4.1, the COVID-19 pandemic had an impact in the way the elicitations were conducted. For the safety of the researcher and research participants, both interview and survey elicitations were completed online and from home where possible in accordance with UK Government and University COVID-19 regulations and guidelines at the time.

4.3 Survey Result Analysis

The way the survey was originally structured was split into three areas of analysis:

- Respondent demography – analysis of questions Q1 to Q5 was used to define and assess each respondent and their experience in relation to the research topic;

- Research questions – analysis of questions Q6 to Q15 directly assessed the research questions and hypothesis defined in this chapter;

- Hypothesis proposal – analysis of questions Q16 to Q18 assessed the reactions to and opinions of the research direction and proposal.

There was a mixture of qualitative (questions Q13, Q15 and Q18) and quantitative (all other questions) in the survey which were analysed separately. Qualitative questions (Q13, Q15 and Q18) were analysed using a condensed thematic analysis method parallel to the thematic analysis of the interview responses. These helped to explain the quantitative survey results and formed links between the survey and interview results.

4.3.1 Respondent Demography

In total, 26 responses to the survey were received. The sample size of participants is small, and further work is needed to substantiate the following results with a larger sample size to generate more reliable findings. 23 of these responses came from within the UK, and three from Canada. Table 4.4 and Figure 4.1 show the distribution of these respondents from their respective regions within each country. As this study is primarily UK-based, the responses from the UK and Canada are segmented and the data analysis primarily focuses on the responses from the UK. Whilst few, the Canadian responses are still used for comparative purposes where appropriate.

Table 4.4 Origin of survey respondents

Country	Region	Respondents
United Kingdom	East Midlands	3
	East of England	5
	North East	1
	Scotland	2
	South East	4
	West Midlands	2
	Yorkshire and the Humber	2
	Undisclosed	*4*
Canada	New Brunswick	1
	Ontario	2

Of the respondents who submitted information on their job roles, ten characterised themselves as consultants, five academics, five planners and two engineers. The remaining individuals consisted of a transport economist, international transport programme manager and a director of a railway infrastructure group. Based on the respondent’s employer and job role information, all 26 respondents are currently in roles with either direct involvement in, or that have a strong relationship with, the transportation planning discipline.

Figure 4.1 Distribution of respondent origins from within the UK by region

The majority (17) of respondents described themselves in senior roles including self-described “directors”, “managers” and “professors”. The remaining respondent’s job role descriptions adequately justified their relevant experience to answer the survey questions.

The survey was only distributed to and via transportation/planning-related networks. Given the described demography of the respondents and the high level of quality and thoroughness of each response, there is no reason to discount any of the 26 responses to the survey. Therefore, all 26 responses are analysed.

To protect the anonymity of respondents, specific respondent locations, employer details and job role information were omitted from the analysis.

4.3.2 Research Questions and Hypothesis

To complete an analysis of the survey results, the original research questions were considered (Heeringa et al., 2010). Table 4.5 shows how the different survey questions looked to answer the research questions of this chapter. The survey was structured based on themes (including CAEVs and transport planning) to provide the respondent with an understandable flow of questions by keeping questions regarding similar topics together. As such, the survey questions are not chronological when aligned with the research questions.

The following analysis brought together the survey questions relevant to their respective research questions as shown in Table 4.5. Each of the following sub-sections reviews each survey question individually and assesses the combined response to the research question at the end.

Table 4.5 Relationships between research and survey questions

Research Questions	Survey Questions
A. To what extent is the implementation of rural CAEV technology currently a priority for transport planning professionals?	6. Please rank the following priority areas for rural transport in your region, with the highest priority first.
	7. To what extent do you agree that urban transport planning takes priority over rural transport planning?
	8. To what extent do you agree that future transport systems and technologies are considered when planning rural transport systems and infrastructure?
	9.To what extent are CAEVs considered in rural transport planning in your region?
B. To what extent do rural transport planners believe that CAEVs are an important factor for the consideration of future sustainable transport solutions?	12. To what extent do you agree that CAEVs will improve the following aspects of rural transport?
	13. Please state any other areas of rural transport that you believe CAEVs will improve.
C. To what extent do rural transport planners understand CAEV technologies and their infrastructural requirements?	10. To what extent are the following CAEV supporting infrastructures considered in rural transport planning?
	11. Please rank the following barriers to rural CAEV implementation, with the largest barrier to implementation first.
	14. In your opinion, how well are CAEVs, their technologies, and their planning requirements understood amongst the rural transport planning industry?
	15. Please suggest how the understanding of CAEV planning requirements could be improved?

Given the subjective nature of the survey questioning, a number of weighted scores were applied to some of the survey results. This was done so that they could be assessed in a quantitative manner. Ranking questions, Q6 and Q11, were given scores from 10 to 1 and 7 to 1 respectively, based on the ranking position of the options given. Details of the ranking weights for both Q6 and Q11 are provided in the analysis. For questions Q7, Q8 and Q12 the weightings for the categories used are shown in Table 4.6. For questions Q9, Q10, Q14, Q16 and Q17 the weightings for the categories used are applied as shown in Table 4.7.

Table 4.6 Weighted categories for Q7, Q8 and Q12

Weighted Score	Q7, Q8, Q12 categories
-2	Strongly disagree
-1	Disagree
0	Neutral (neither agree nor disagree)
1	Agree
2	Strongly agree

Table 4.7 Weighted categories for Q9, Q10, Q14, Q16 and Q17

Weighted Score	Q9, Q10 categories	Q14 categories	Q16, Q17 categories
0	Never considered	Not understood	Not useful
1	Rarely considered	Rarely understood	Slightly useful
2	Sometimes considered	Sometimes understood	Useful
3	Always considered	Completely understood	Extremely useful

4.3.3 Research Question A

To what extent is the implementation of rural CAEV technology currently a priority for transport planning professionals?

Q6: Please rank the following priority areas for rural transport in your region, with the highest priority first: accessibility, affordability, automation, communications infrastructure, environment quality, maintenance of infrastructure, public transport services, quality of infrastructure, safety, sustainability.

Question 6 (Q6) aimed to determine the areas of rural transport planning that were most important to rural transport planners. The options consisted of a mix of transport elements based on those in previous chapters regarding rural transport poverty, sustainability and CAEV technologies.

Overall results (inclusive of UK and Canadian responses) show the highest priority areas for rural transport was improving *accessibility* with 50% of respondents selecting this as their first choice prioirty (Figure 4.2). *Affordability* and *safety* also ranked highly, with *safety* being a more common first choice but having a greater range of responses, with some ranking *safety* their lowest priority.

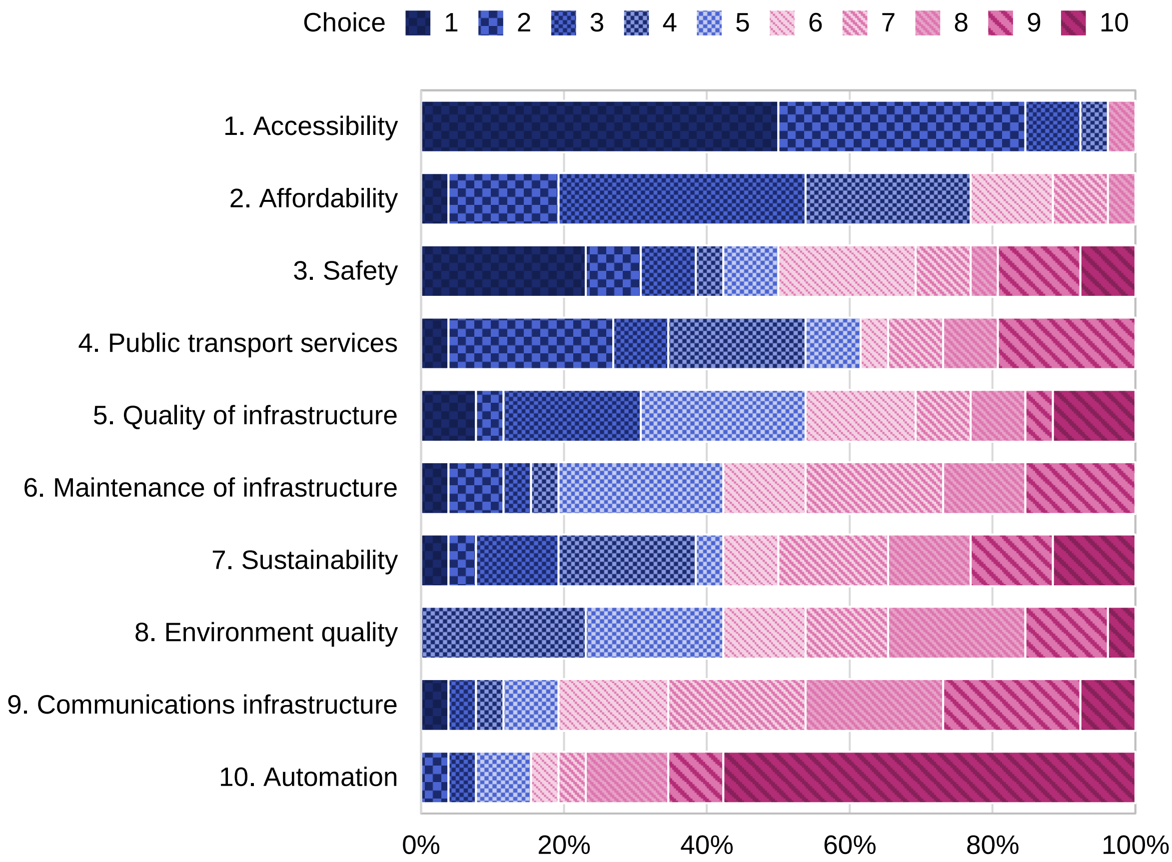


Figure 4.2 Ranked priority areas for rural transport – overall results

Assigning each choice a weighted score from 10 to 1, with 10 being the score for first place prioirty, the distribution of rankings was assessed. For the UK-only results in Table 4.8 and Figure 4.3, the order of priority areas changed slightly to that of Figure 4.2, with *public transport services* overcoming *safety* by 10 points. Still, *accessibility* remained the highest ranked priority, with *affordability* the next most significant. As discussed in previous chapters, affordability is recognised as a component of accessibility and these results indicate that this relationship holds true amongst transport planners. *Public transport services* was the next highest ranked, which again relates to accessibility, given that the frequency and quality of public transport services will improve accessibility to those who the service is available for. *Safety* was the fourth most significant, which could have been expected as, once an accessible and affordable service can be provided, this service would need to be safe to use.

Table 4.8 Ranked priority areas for rural transport – weighted scores and statistics – UK

Option	Total Score	Rank	Mean	Median	Mode	Range
Accessibility	210	1	9.1	9.0	10.0	7.0
Affordability	168	2	7.3	8.0	8.0	7.0
Public transport services	143	3	6.2	7.0	9.0	8.0
Safety	133	4	5.8	5.0	10.0	9.0
Quality of infrastructure	120	5	5.2	5.0	6.0	9.0
Sustainability	117	6	5.1	5.0	7.0	9.0
Maintenance of infrastructure	109	7	4.7	4.0	4.0	8.0
Environment quality	108	8	4.7	5.0	6.0	6.0
Communications infrastructure	95	9	4.1	4.0	4.0	9.0
Automation	62	10	2.7	1.0	1.0	8.0

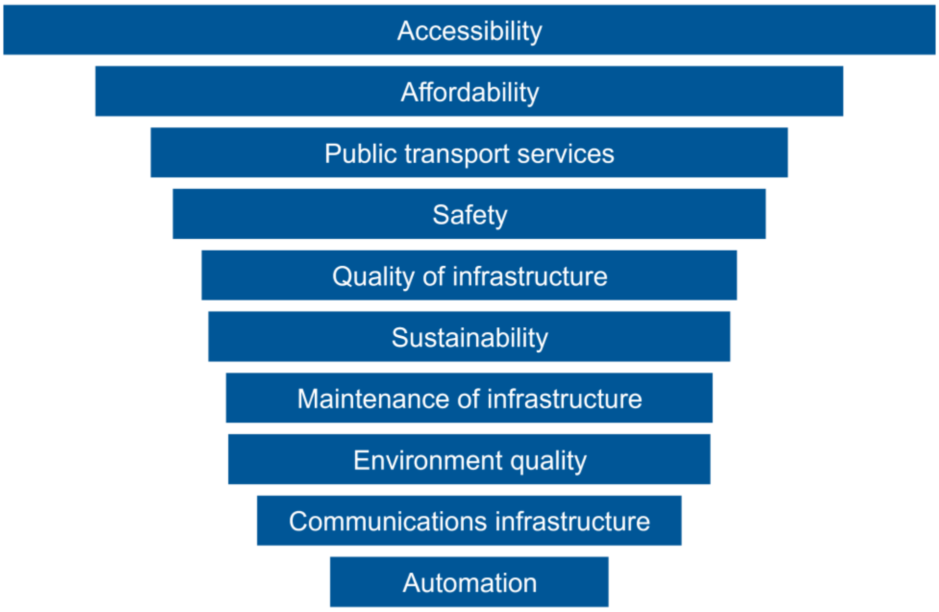


Figure 4.3 Ranked priority areas for rural transport - weighted distribution - UK

Quality of infrastructure, *sustainabiity*, *maintenance of infrastructure* and *environment quality* all ranked within 12 points of each other and can be grouped as similarly equal priorities in transport planning. *Sustainability* is the odd one out of the list of ten priorities as it is a non-specific element that is relevant across all fields and disciplines. With it ranked in sixth place, it shows an awareness of sustainability within transport planning, however it would seem that providing transport solutions that work (meaning they are accessible and safe) takes prioirty over whether or not the solution is a sustainable one. In this case, sustainability is taken to mean a balanced solution across economic, social and environmental domains. The eighth ranked *environment quality* suggests how the three sustainable domains are prioritised within transport planning, with social factors such as *accessibility* and *safety*, and the economic factor of *affordability*, ranked well above *environment quality*.

Finally, *communications infrastructure* was ranked low, with *automation* ranked the lowest prioirty by a significant amount. 57% of UK respondents ranked this their lowest priority. Whilst the other priority areas could be seen as more traditional in their relation to transport methods and practice, these lowest ranked elements relate directly to emerging transport technologies, specifically CAEVs. *Communications infrastructure* may have scored more highly than *automation* due to the lack of general communications infrastructure in rural areas, but it remains low due to the current direct relevance between communciation and transportation infrastructure.

Q7. To what extent do you agree that urban transport planning takes priority over rural transport planning?

74% of UK respondents *agreed* or *strongly agreed* that urban transport planning takes priority over rural transport planning, with no respondents *strongly disagreeing* (Figure 4.4). No distinct pattern emerged regarding the locations of the respondents and their responses to this question. This finding supports the recurring theme described in this thesis of an urban-rural transport divide. Figure 4.4 describes the low priority of rural transport planning broadly amongst the general transport planning community. Against this background Q8 and Q9 further investigated the priorities of more specific elements of rural transportation.

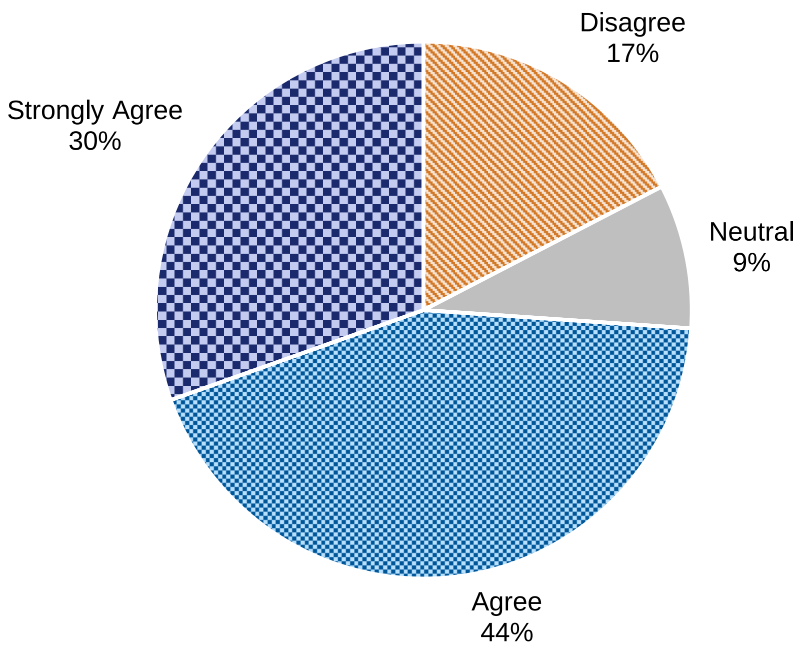


Figure 4.4 Extent of agreement that urban transport planning takes priority over rural transport planning – UK

Q8. To what extent do you agree that future transport systems and technologies are considered when planning rural transport systems and infrastructure?

Only 12% *agreed* that future transport systems and technologies were considered when planning rural transport systems and infrastructure (Figure 4.5). 50% *disagreed* that future transport systems were considered whereas 38% *neither agreed nor disagreed*, suggesting that they are uncertain whether consideration takes place. Alternatively, they may see the consideration of future transport technologies in some cases, but not in all cases. On average there was a mild disagreement to the question amongst respondents.

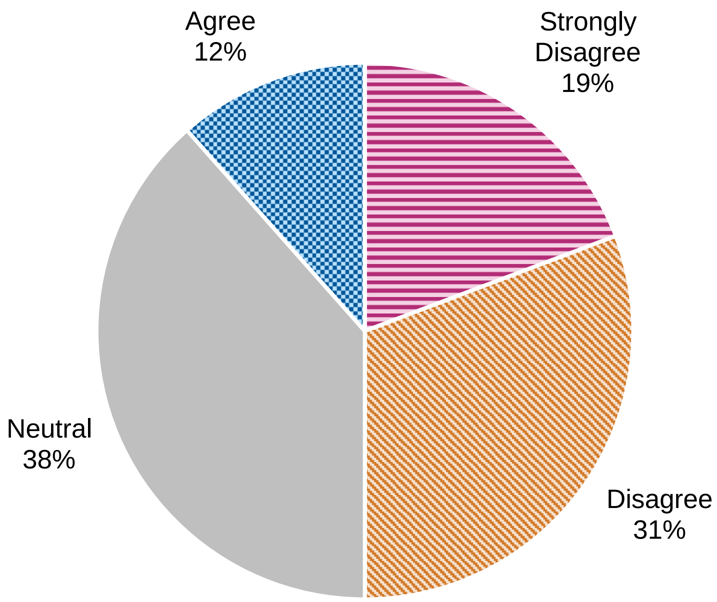


Figure 4.5 Extent of agreement that future transport systems and technologies are considered when planning rural transport systems and infrastructure – UK

Q9. To what extent are CAEVs considered in rural transport planning in your region?

In an extension to Q8, Q9 asks specifically about the consideration of CAEVs, and the results therefore directly addressed Research Question A. The results are shown in Figure 4.6. Responses to Q9 were more negative, with 85% of respondents expressing that CAEVs are *never* or *rarely considered* in rural transport planning. However, slightly more respondents *agreed* with Q9 than Q8, despite an overall stronger disagreement. All the respondents that *agreed* with Q8 believed that CAEVs were *sometimes considered* in rural transport planning. Typically, responses referred to SAE level 4 autonomy.

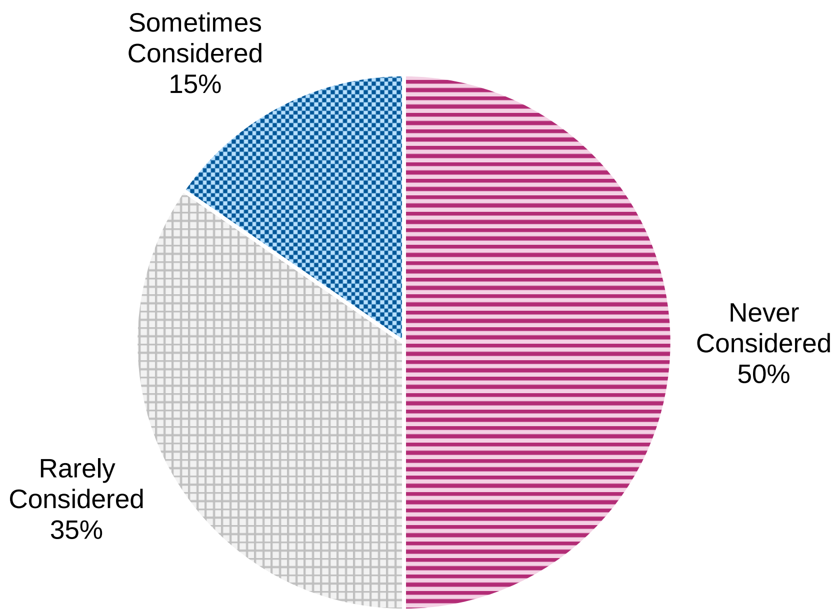


Figure 4.6 Extent of consideration of CAEVs in rural transport planning – UK

4.3.4 Research Question B

To what extent do rural transport planners believe that CAEVs are an important factor for the consideration of future sustainable transport solutions?

Q12. To what extent do you agree that CAEVs will improve the following aspects of rural transport?

Q12 asks respondents to agree or disagree whether rural transport accessibility, affordability, environment quality, public transport services, safety and sustainability will be improved by CAEVs. The overall results showed a tendency for respondents to *agree* that CAEVs will improve most aspects of rural transportation. Typically, responses referred to SAE level 4 autonomy.

UK specific results, following a weighted analysis of each response as described in Given the subjective nature of the survey questioning, a number of weighted scores were applied to some of the survey results. This was done so that they could be assessed in a quantitative manner. Ranking questions, Q6 and Q11, were given scores from 10 to 1 and 7 to 1 respectively, based on the ranking position of the options given. Details of the ranking weights for both Q6 and Q11 are provided in the analysis. For questions Q7, Q8 and Q12 the weightings for the categories used are shown in Table 4.6. For questions Q9, Q10, Q14, Q16 and Q17 the weightings for the categories used are applied as shown in Table 4.7.

Table 4.6, showed a cautiously optimistic consensus for each of the transport aspects, excluding *affordability* for which there was a slight disagreement (Figure 4.7). These cautious results could have been partly due to a lack of understanding amongst transport planners, which is identified later in Q14, who were not fully convinced of the technology but have heard about it’s potential.

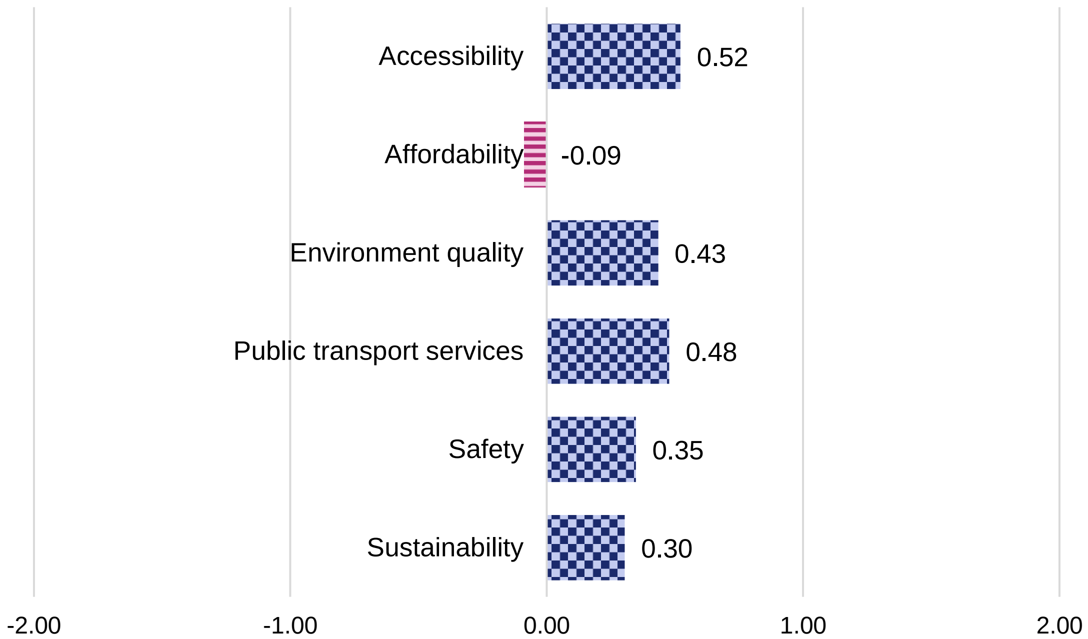


Figure 4.7 Average scores of the extent to which CAEVs will improve different aspects of rural transport - UK

Notably, *accessibility* and *public transport services* were ranked the most highly. They were also ranked highly in Q6 which asked for priority areas for rural transport. Therefore, the results to this question have highlighted a disconnect between the needs of rural areas in relation to transport, the priority of CAEVs in terms of their required technologies and infrastructure (automation, communications, readable roads and charging infrastructure), and the perceived benefits CAEVs could bring.

Question 13. Please state any other areas of rural transport that you believe CAEVs will improve.

Table 4.9 summarises the responses to Q13 which were analysed by coding similar qualitative ideas into group nodes. Typically, responses referred to SAE level 4 autonomy. The highlight of Table 4.9 is the addition of *flexibility* as a benefit of CAEVs, seen as a separate benefit to *accessibility*. This is possibly because as accessibility can be viewed as a fundamental concept for rural societies, which they have as a basic requirement. Flexibility, on the other hand, may be seen as an enhanced version of accessibility that focuses on maximising convenience, as is a target of many urban transport systems.

Table 4.9 Q13 - Coded improvements CAEVs could bring to rural transportation

Improvement	Frequency	Summary
Flexibility	9	Mainly referred to in relation to public transport options, providing people with flexibility ranging from an individual vehicle level to flexible fleet and types of CAEV options.
Improved infrastructure	3	CAEVs could result in less stress on existing infrastructures and provide more opportunities for physical infrastructure improvements and integration for modal shift.
Economics	3	Reducing the personal costs of transport whilst bringing wider economic benefits through improved connectivity.
Ease of planning	2	Improved vehicle and system efficiencies could aid route planning and prioritisation.

Other	3	Improved transport technologies, access to information, environmental benefits.

Despite affordability having ranked the worst in Q12, it is referred to several times in Q13, usually in association with another improvement being discussed. This suggests that the transport planners could see positive economic potential for CAEVs but in their current state they are an expensive solution for the user.

4.3.5 Research Question C

To what extent do rural transport planners understand CAEV technologies and their infrastructural requirements?

Q10. To what extent are the following CAEV supporting infrastructures considered in rural transport planning?

The CAEV supporting infrastructure in Q10 referred to electric charging infrastructure; machine readable road features, marking and signage; and wireless communication networks. Generally, machine-readable roads were not considered by transport planners, electric charging infrastructure was rarely considered, and wireless communications were considered only marginally more, although this received the most diverse range of opinions of the three.

By assigning scores of 0, 1, 2 and 3 to each ranked response from *not considered* to *always considered* respectively (see Table 4.7), an average result for each of the three infrastructures was inferred. Averaging for the UK only data, scores of 1.39 (*rarely* to *sometimes considered*), 0.35 (*not* to *rarely considered*) and 1.43 (*rarely* to *sometimes considered*) for electric charging infrastructure; machine readable road features, markings and signage; and wireless communication infrastructure respectively were calculated (Figure 4.8).

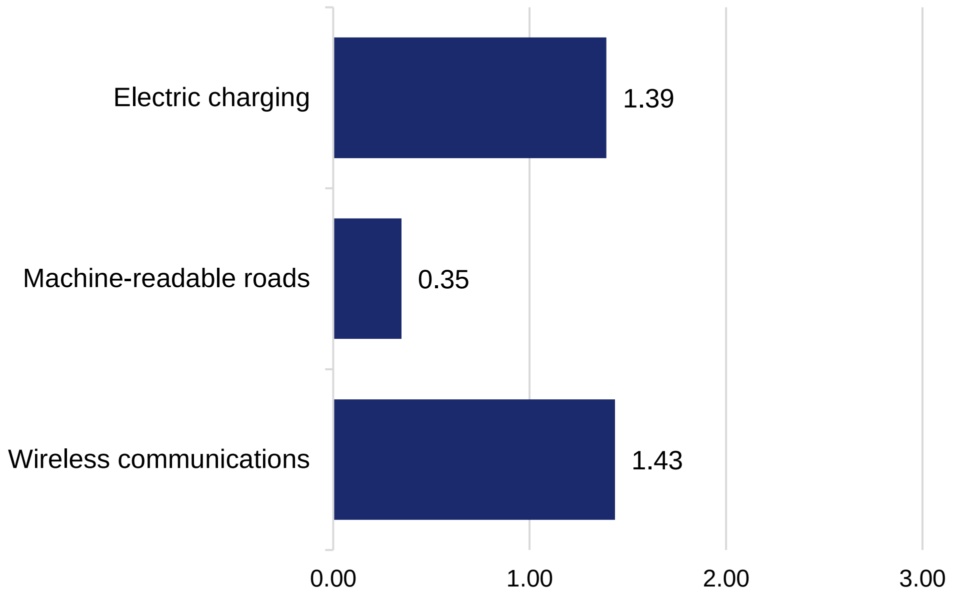


Figure 4.8 Average scores of the extent of consideration for three CAEV supporting infrastructures – UK

This has highlighted a gap in consideration between machine readable roads, and electric charging infrastructure and wireless communications. Machine readable roads were recognised in Chapter 2 and Chapter 3 as an important infrastructure requirement for rural, road-based CAEVs. However, perception technologies continue to improve and therefore the extent to which road infrastructure needs to be "machine readable" is reducing. Whilst electric charging infrastructure and wireless communications infrastructure are also required for CAEVs to operate successfully, these technologies also feature in many currently active personal road vehicles. For example, many EVs currently on the roads require charging infrastructure, and many feature vehicle software that receive over-the-air updates. As such, these two infrastructures would realistically be more pressing for rural transport planners. Despite this, both remained *rarely considered*.

Q11. Please rank the following barriers to rural CAEV implementation, with the largest barrier to implementation first: communications infrastructure, electric charging infrastructure, government/local authority acceptance, industry acceptance, machine-readable road features, public acceptance, regulation and law.

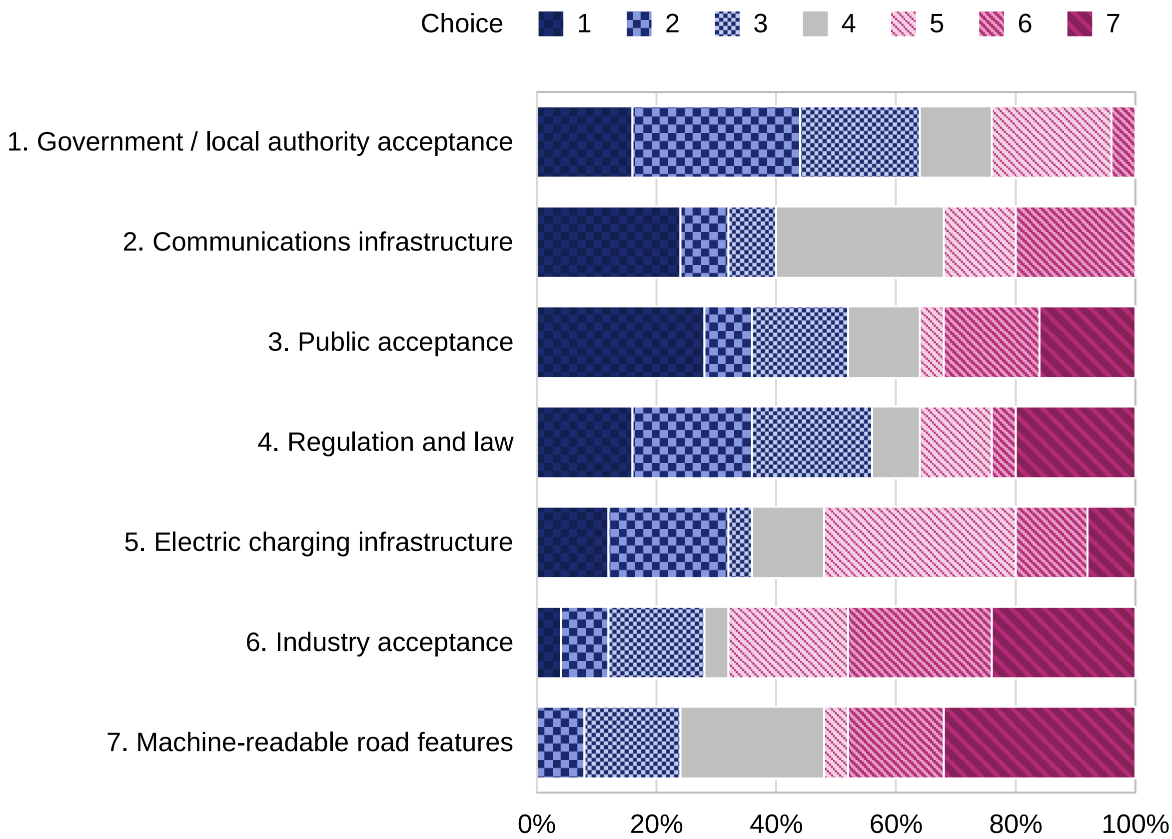


Figure 4.9 Ranked barriers to rural CAEV implementation - overall results

The overall results for Q11 are shown in Figure 4.9. The standout result from Q11 is that *public acceptance* was the most conflicted barrier with 27% of respondents noting this as their first-choice barrier and 31% ranking it their least or second to least barrier to rural CAEV implementation. Breaking the results down into UK and Canadian responses, a conflict was identified between the two on the matter of *public acceptance* with Canadians ranking it highly compared to UK respondents (Figure 4.10). The remaining barriers stayed in the same order for both countries.

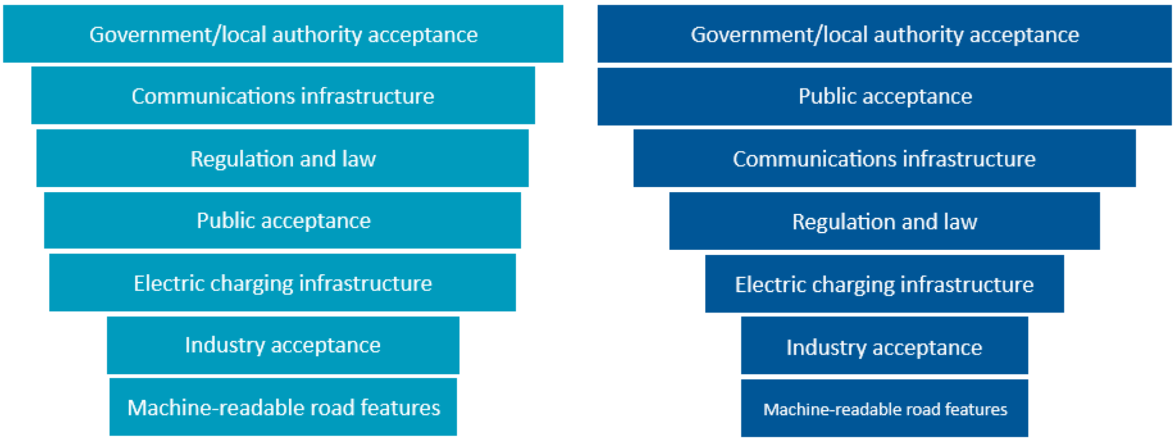


Figure 4.10 Ranked priority barriers to rural CAEV implementation - weighted distribution - UK (left) and Canada (right)

For the UK data three distinct groups were identified. Firstly, *government acceptance* stood out on its own as the greatest barrier to CAEV implementation. Then *communications*, *regulation*, *public acceptance* and *electric charging infrastructure* were the next group with similar significance. *Industry acceptance* and *machine-readable roads* were seen as the least significant barriers to CAEV implementation. A similar trend was identified from the Canadian responses, except for *public acceptance* which was ranked equally highly to *government acceptance*.

Table 4.10 breaks down the results from Q11 for the UK responses. Interestingly, the range of responses identified for all of the barriers to rural CAEV implementation was at least five, and in four cases it was the maximum range of six. A range of six meant that at least one respondent thought a barrier was the most significant (with a score of 7) and at least one other respondent thought that the same barrier was the least significant (with a score of 1). The large ranges across the barriers have shown that there is a lack of unity within the rural transport planning sector on the issue of barriers to CAEV development. There could be several reasons behind this finding, including a lack of universal understanding of these barriers, difference in opinion based on local circumstance, or that all the barriers listed are significant based on the different perspectives and experiences of individual respondents. It is unclear to which level of autonomy respondents were referring and responses likely ranged from referencing SAE levels 3, 4 and 5.

Table 4.10 Ranked barriers to rural CAEV implementation - weighted scores and statistics – UK

Barrier	Score	Rank	Mean	Median	Mode	Range
Government/local authority acceptance	108	1	4.9	5.0	3.0	5.0
Communications infrastructure	97	2	4.4	4.0	4.0	5.0
Public acceptance	95	3	4.2	4.5	7.0	6.0
Regulation and law	92	4	4.3	5.0	6.0	6.0
Electric charging infrastructure	90	5	4.1	3.5	3.0	6.0
Industry acceptance	68	6	3.1	3.0	1.0	6.0
Machine-readable road features	67	7	3.0	3.5	4.0	5.0

It is also of note that the modal averages for *public acceptance* and *regulation and law* were seven and six respectively, which were the two highest scores that can be given. This has indicated that these two barriers would be recognised as the most significant barriers through a popular vote. Despite this, these barriers have been ranked 3rd and 4th respectively, due to the range of other responses.

Referencing the Q10 results, the ranking of the infrastructure barriers correlated with the level of consideration of each barrier. Wireless *communications infrastructure* ranked the most important barrier of the three and was also, marginally, the most considered for implementation. Whereas the lowest ranked, *machine-readable roads*, was also the least considered infrastructure requirement.

Q14. In your opinion, how well are CAEVs, their technologies, and their planning requirements understood amongst the rural transport planning industry?

96% of UK respondents noted that any understanding of CAEV technologies amongst the transport planning industry was either rare or entirely absent (Figure 4.11). Most of these were the same respondents who reacted similarly to Q9 believing that CAEVs were not, or rarely, considered amongst transport planning professionals.

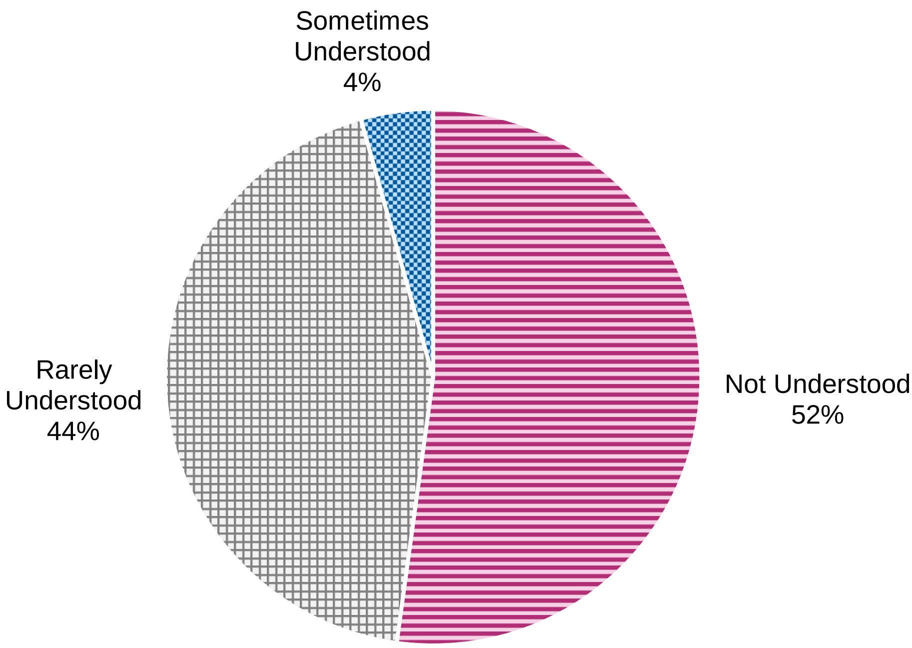


Figure 4.11 Extent of understanding of CAEVs amongst the rural transport planning industry – UK

Q14 has directly addressed Research Question C by highlighting that there is a general lack of understanding of CAEVs amongst rural transport planners. The reasoning for the range of responses to both Q10 and Q11 can be inferred from Figure 4.11 where the lack of understanding of CAEVs may explain the range of scores, and associated uncertainty, around CAEV infrastructure and barriers to implementation. Contributing to this lack of clarity could also be that the level of autonomy was not specified in this and the following question.

Q15. Please suggest how the understanding of CAEV planning requirements could be improved.

Table 4.11 summarises the responses to Q15 which were analysed by coding similar qualitative ideas into group nodes. The frequency column indicates how often that idea, or equivalent ideas were suggested. Note that the frequency of the ideas exceeds the total number of respondents due to some respondents offering multiple suggestions, but also due to overlapping suggestions such as written proof of technology.

Table 4.11 Coded suggestions to improve the understanding of CAEV planning requirements

Suggestion	Frequency	Summary
Stakeholder engagement	7	Engagement between planners and stakeholders involved specifically in CAEV and technological development to encourage knowledge sharing and spread awareness.
Proof of technology	6	Experimentation and demonstration to prove that CAEV and related technologies actually work, ideally in real-world conditions. Proof of safety and a range of benefits.
Formal education	6	Traditional education methods such as CPD and training but also including written forms of communication such as formal guidelines for best practice.
Case studies	5	Completed case studies showing proof of implementation in specific scenarios, can either be in written form or demonstrated first-hand.
Economic investment	5	Economic investment in CAEV trails and projects helps to raise awareness and understanding, particularly large and high-profile investments.
Policy change	4	Formal changes to policy and legislation in effect force planners to acknowledge and understand the requirements for CAEVs.
Other	2	Physical and interactive modelling; generic knowledge sharing.

4.3.6 Perspectives on Hypothesis Proposal

The final part of the research survey requested that respondents react to the hypothesis proposal described at the start of Chapter 4. The proposal was presented in the survey as follows:

> *"This research project proposes to develop a simple set of indicators to aid rural transport planners in preparing for CAEV implementation. These indicators are to be visualised in a Geographic Information System (GIS) to highlight specific areas that are lacking specific requirements for CAEV implementation."*

Q16. How useful do you believe such a set of indicators would be for rural transport planners?

Across all responses 75% rated the index proposal highly, of which 89% responded *useful* or above to Q17. Views were equivalent across UK and Canadian responses.

Q17. How useful would it be if these indicators were presented as a layered GIS that highlighted areas of need depending on their geographic indicator results?

Again, 75% responded with *useful* or *extremely useful*, with *extremely useful* receiving one more vote than in Q16. The same respondents that voted for *not useful* in Q16, voted *not useful* again in Q17. Overall responses to both Q16 and Q17 are shown in Figure 4.12.

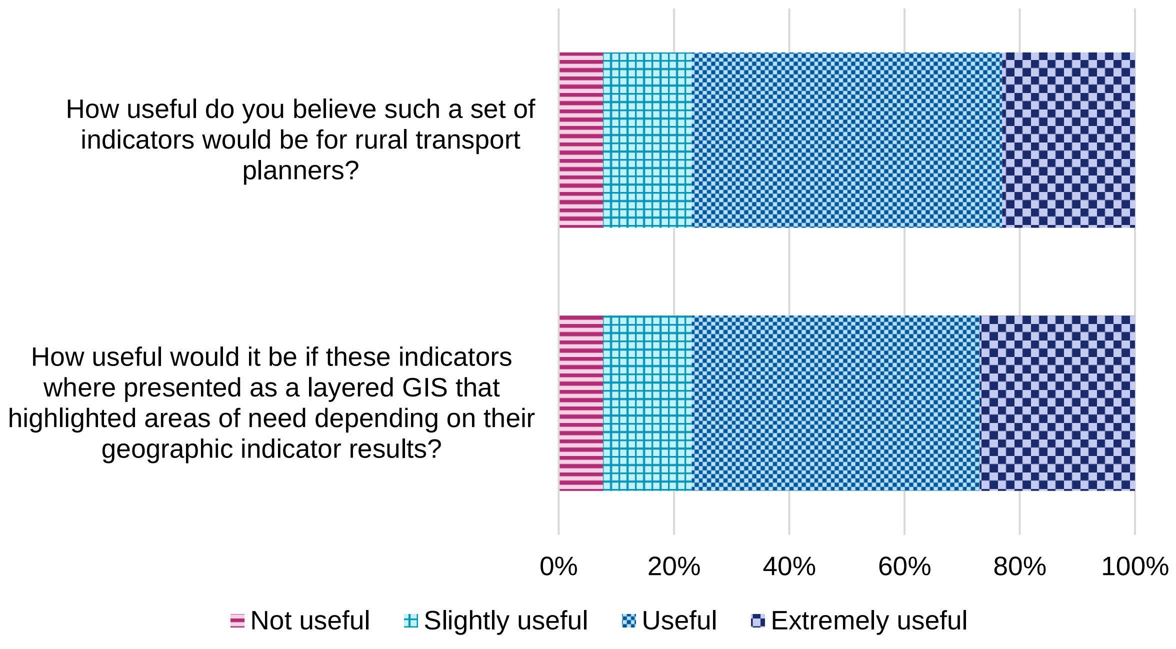


Figure 4.12 Opinions on the hypothesis proposal - overall results

92% of respondents believed that both elements of the hypothesis proposal would be useful to some extent. This provided an overwhelmingly positive response to the research proposal. In further support of the proposal was the lack of understanding amongst transport planners regarding CAEVs and their infrastructure requirements, which was identified in the survey analysis and specifically highlighted by the results in Figure 4.11.

Q18. Finally, do you have any comments, thoughts, or suggestions regarding this research proposal?

Q18 asked for any further thoughts on comments on the research proposal, offering respondents a chance to offer reasoning for their responses, advise for or criticisms of the research proposal.

There were a range of qualitative responses to Q18. A number of respondents suggested that the consideration of economics was an important aspect of the research, primarily because the implementation of new transport technologies requires investment. In addition, this investment needed to be justified, and historically, rural areas are economically underserved due to poor business cases for investors. One respondent suggested considering developing a "funding model and approach, perhaps with industry partners, to help planners understand how CAEV implementation might be funded, and its operating and maintenance costs paid for." However, this research is a first look at the practicalities of CAEV implementation in rural areas rather than determining the economic requirements for such implementation. One respondent suggested that "there is no realistic prospects of CAVs being taken seriously in planning terms until they are viable and affordable. We are only now embracing electric vehicles and need to focus our efforts on that technology for now."

Two respondents identified the opportunities this study brings to the transport planning profession in that the complexity of rural transport could benefit from a simplified tool at least in the early stages of CAEV implementation. Whilst one respondent identified a wide range of requirements and barriers specific to rural transport environments, they went on to say, "but that's what might make this interesting research in terms of identifying in a very clear and implementable manner what those requirements are."

In addition to the above there were broad suggestions made on how to manage the index and GIS, its use across different environments, and the importance of continued engagement with transport planners throughout development of the project. This was the aim through the application of the index to specific case studies in which the indicators were applied to regions in which there are known contacts in rural transport planning, to aid the development of the proposal. These case studies are investigated in Chapter 6 of this thesis.

4.4 Interview Result Analysis

Whilst originally widely used as a qualitative analytical method in psychology, thematic analysis can be useful across disciplines, particularly in cases using semi-structured interviews, and is seen as a foundational method for qualitative analysis. Thematic analysis is a method for identifying, analysing and reporting themes within data and can be used to organise, describe and interpret different research aspects (Braun and Clarke, 2006).

This thesis will use the recently distinguished *reflexive thematic analysis* (Braun and Clarke, 2019) as a particular thematic analysis approach emphasising the importance of subjectivity as an analytic resource. This demarcation acknowledges the researcher's individual and subjective engagement with the data and it's interpretation (Braun and Clarke, 2020). There are 6 phases of reflexive thematic analysis as described in Table 4.12.

Whilst thematic analysis was performed, the questions from the interview were such as to direct the conversation towards similar topics from the survey as outlined in Table 4.5. The analysis allowed for the identification of themes from across the interviews that were then assessed as to whether and how they could contribute to answering the research questions.

Table 4.12 Phases of reflexive thematic analysis (adapted from Braun and Clarke, 2006)

#	Phase	Description and actions

1	Familiarisation of the data	Understand the depth and breadth of the data collected. This can involve repeated and active reading; searching for patterns and meaning. Transcription of verbal data can be an effective method of familiarisation.
2	Generate initial codes	Codes identify a feature of the data that appears interesting to the analyst and form the basic level of assessment. Systematic assessment of each data item is needed. Code as many potential themes or patterns as possible. Generate a list of ideas and interesting data themes.
3	Search for themes	Sort the codes into potential main themes, sub-themes and miscellaneous themes if some codes don't appear to fit. Start to understand the significance of the themes identified.
4	Review themes	Refinement of candidate themes. Themes should contain meaningfully cohesive data with clear identifiable distinctions between themes. Some themes may need to be reworked or removed entirely. Create a thematic map refining the reviewed themes. Review the original data and codes to assess the appropriateness of the thematic map.
5	Define themes	Define and further refine the themes to present for analysis. Identify the interesting aspects of the data behind the themes, rather than paraphrasing the original data. Write a detailed analysis of each theme and how they fit into the broader data story in relation to the original research aims and questions. Sub-themes can be defined to provide structure for large and complex themes. Themes must be named so that they are immediately understandable.
6	Report	Tell the complicated story of the data in a convincing way to validate the analysis. This must be concise, coherent, logical and interesting. The report must provide sufficient evidence of the themes with simple but vivid examples.

The software tool NVIVO was used to conduct the reflexive thematic analysis of the interview results. It was developed for qualitative researchers to aid in the management, exploration and discovery of data patterns including in the analysis of interview transcriptions and survey results. Each interview transcription was imported into NVIVO and reviewed. Codes were created for each of the items discussed in the interviews using NVIVO's coding functions, based on the elicitor's interpretation of the transcription. Once each transcription had been liberally coded, themes common across the codes were identified by reviewing each code and grouping codes. Several iterations of this process were performed until clear themes and sub-themes were generated. Sub-themes that contained a small number of coded texts were grouped with similarly small but relevant codes to form larger sub-themes to tidy up the data. Each coded piece of text is referred to as a *reference* in the analysis below.

The analysed interview data was split into three overarching topics of discussion:

- Participant details – introductory discussion with the participant to gauge the extent and relevance of their expertise on the subject; 10 distinct references were found on this topic, but were not analysed further as the data contained sensitive personal information, although a summary of the participants can be found below;

- Rural CAEV implementation – the research topic of this thesis; 388 distinct references were found on this topic in the analysis;

- Hypothesis proposal – regarding the resulting CARTI solution; 37 distinct references were found on this topic.

4.4.1 Participant Summary

Five interviews took place following the interview participant selection process within the defined interview period of the research project. Again, this sample size could be considered statistically insignificant given the broad range of experience available across the UK on the subject matter. The COVID-19 outbreak was a factor here limiting the ability for the researcher to meet with potential participants. COVID also limited the ability to hold group workshops where preferably ideas could have been shared and discussed resulting in richer findings in this chapter.

Table 4.13 records the details of these participants. Each participant was assigned a Greek letter to protect their identity alongside a summary of their expertise to justify their relevance to this research. The interview duration and total number of references extracted during the thematic analysis were also recorded.

Discussions with these five participants covered a range of subject matter related to this research project. Fundamentally, and in relation to the core topic of rural CAEV implementation, CAEV technologies, associated infrastructure, social interactions and attitudes, economics, and the environment were collectively covered by the five participants.

Table 4.13 Interview participant details

Participant Code	Area of Expertise	Interview Duration (MM:SS)	Total References
α	CAEV Systems Engineering and Applications	37:00	322
β	Electrification and Vehicle Systems Research	32:10	193
γ	Rural and Future Mobility Research	27:10	260
δ	Human Factors and CAEV Interactions Research	37:07	216
ε	Transport Planning and Highways Engineering	42:56	334

4.4.2 Rural CAEV Implementation Themes and Sub-Themes

As expected, the most significant discussions took place around the rural implementation of CAEVs. Within this topic, themes were identified and further detailed sub-themes within them. It was broadly accepted that the content of these discussions referred to level 4 autonomy.

Figure 4.13 shows the themes colour coded with sub-themes within them. The size of each box represents the extent to which each sub-theme was discussed across the interviews based on the number of references identified within that sub-theme in the analysis. The four major themes of rural CAEV implementation were *challenges*, *benefits*, current and potential *applications* and an outlying *urban* theme that occurred across the interviews despite the intention to focus on rural issues. Each of these themes, apart from *urban*, contained several sub-themes. As references to rural CAEV *challenges* were the most recurring, the *challenges* sub-themes have been further grouped by whether they related to environmental/infrastructural, institutional, economic, technological or social challenges.

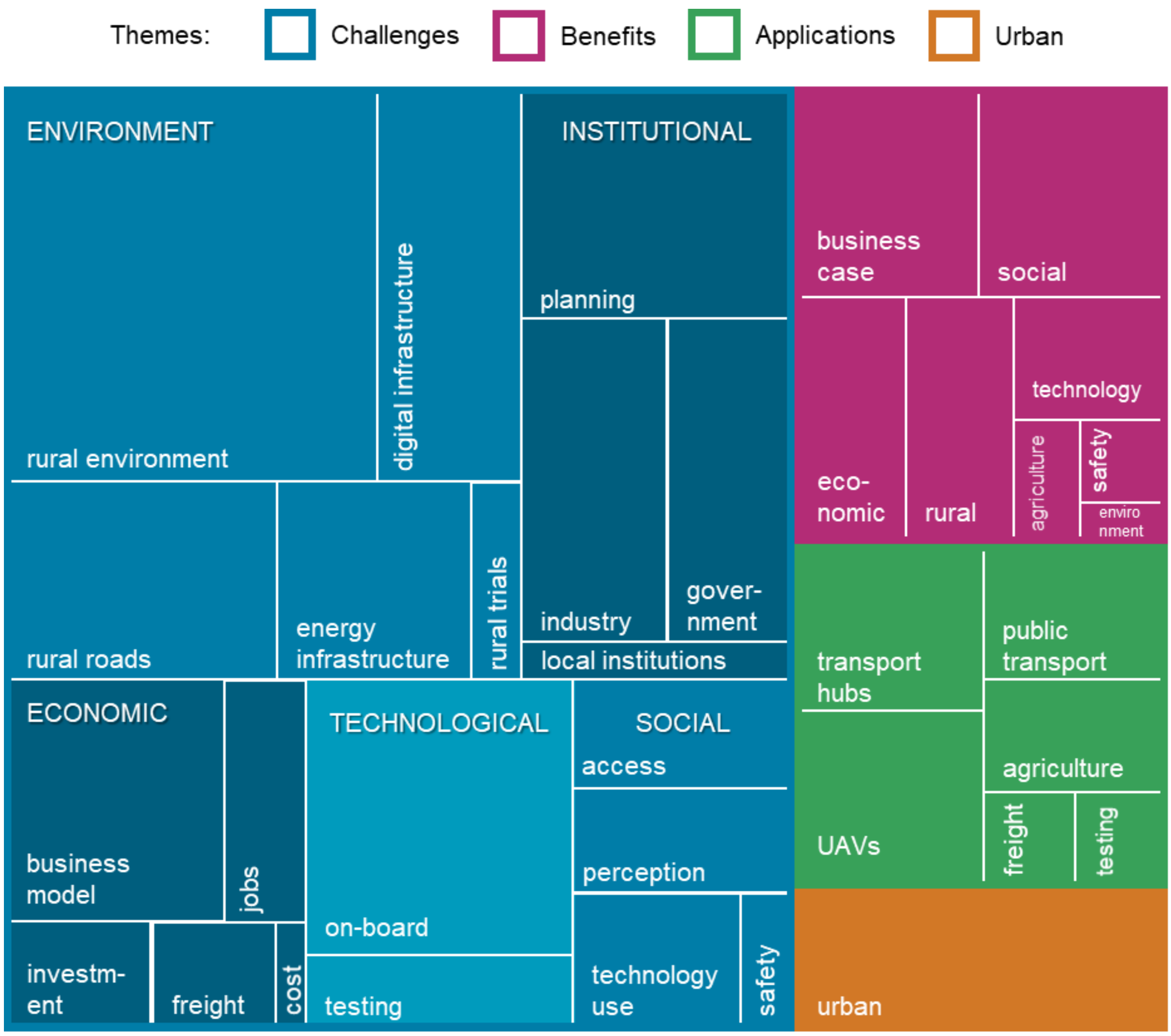


Figure 4.13 Themes and sub-themes identified within the wider rural implementation of CAEVs topic

4.4.3 Rural CAEV Implementation Challenges

The challenges theme was the most discussed theme across each interview, although the extent to which each sub-theme was discussed varied. Figure 4.14 shows the extent of conversation of each sub-theme with each participant. Whilst measured by the number of references, the resulting absolute figures are not particularly relevant. What is relevant is that Figure 4.14 gives a good indication of the themes and content discussed with each participant. The extent of the chart does not however determine which participant contributed the most, nor does it highlight which participants went into the most detail. Figure 4.14 purely indicates the number of separate references to the *challenge's* sub-themes based on the elicitor's interpretation.

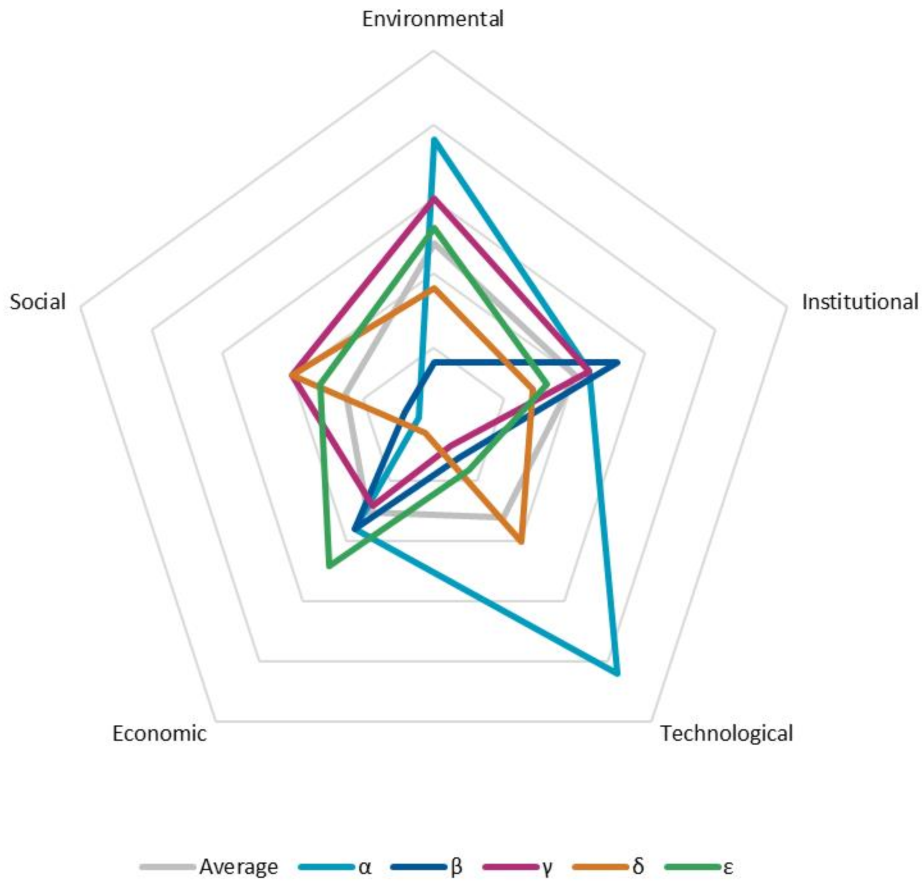


Figure 4.14 References to the Challenges Sub-Themes by Interview Participant

For example, Participant ɑ recorded the greatest number of overall references. Participant ɑ preferred to concentrate on discussing environmental and technological challenges to rural CAEV implementation. Compared to the other participants, Figure 4.14 shows that Participant ɑ discussed a large range of individual, although related challenges. In contrast, Participant β recorded the smallest number of references and mainly discussed economic and institutional challenges. However, whilst the extremities of their radar area are well below that of Participant ɑ, this does not mean they contributed less or had less knowledge. In fact, this indicates that they discussed individual subjects in greater detail, resulting in fewer but more detailed references to specific areas of knowledge.

Environmental

The interview results show that *environmental challenges* were the most referenced. This likely arose because of the specific research focus on the implementation of CAEVs in the rural environment. These challenges included those generically recognised as rural and rural transport challenges, many of which have already been described in Chapter 1 of this thesis. Participant α summarised the extent of rural-based challenges well by describing the "patchy, underserved nature" of rural areas. This description was applicable across all the participants' references to rural environment challenges, be that a challenge related to population distribution, internet coverage, transport network service areas, or road and infrastructure quality and consistency.

Some of the more specific rural environment challenges described were those related to the distribution and quality of rural infrastructure, including the roads themselves, digital and energy infrastructure. Both Participants α and δ referred to poor but also varied road infrastructure quality including "white lines… appearing and disappearing", a subject investigated in Chapter 3. Participant γ recalled an issue from a previous project where "they admitted that they hadn't really considered rural areas because of the need of so much density of data to map the roads". Similarly, Participant δ also referred to the complexity and shear total length of rural road networks, "we just have too many roads", as an infrastructure challenge in relation to the potential roll out of V2I and other infrastructure-based communication technologies.

Due to the scale of rural road infrastructure, digital infrastructure was also a commonly referenced example of a rural environment challenge.

> *"There are so many tens of thousands of miles of rural roads I don't think you'd ever sensibly roll out any fixed [digital or communications] infrastructure."*

Participant α

4G internet coverage was viewed as the only current realistic alternative to fixed internet connectivity but needed to be "relatively reliable" (Participant α).

However, as Participant γ noted "you can't afford for [the 4G signal] to just suddenly go in a valley" and that providing reliable 4G connectivity to "that very last 5%... in the more remote areas" will be a "real challenge".

Finally, the distribution of rural energy infrastructure was identified as a similar challenge. Consistent with the assumptions described in this thesis, each participant referred to autonomous vehicles as almost certainly being battery-electric and therefore a major barrier to rural implementation is "battery power charging" (Participant ε). Participant β agreed that "there is a missing power charging infrastructure".

> *"In rural areas a challenge will always be the distance you are likely to go and… the likelihood is that the power grid will not be either strong or in the right places that you need it."*

Participant β

Institutional

The next most referenced challenge sub-theme were institutional challenges, relating to local planning authorities, private transport and technology industries, and UK government with local institutions, such as universities, briefly mentioned.

Participant α mentioned that there was no "guidance available" for local planning authorities on CAEV implementation. This related to the uncertainty around CAEV technologies and technological progress as well as timescales of when and if this technology will be available. Participant β suggested that CAEV implementation would be "based on local decisions" as there is currently no "form of government politicisation" on the direction of CAEVs, their technologies and energy infrastructure. Participant γ echoed this and explained that "there is so much diversity of need [in rural areas] it's down to local authorities" to assess the requirements, identify barriers and opportunities and prioritise areas of investment. However, "the danger of that is you get a more fragmented delivery of technology" and Participant δ notes that there are "too many different county councils all doing their own thing". Participant ε further explained that district highway authorities can suggest technical specifications for local planning authorities but "to get [local authorities] to all work together may be problematic because they are very localised…, very traditional [and] most of them are conservative" which is a particular problem when highway authorities cover both urban and rural areas.

As Participant ɑ described, local authorities consist of "very small teams with a huge variety of responsibilities" and these responsibilities vary depending on local circumstance. In terms of progress towards CAEV implementation or even consideration, Participant ɑ suggested that "it depends how close they've been to the technology" and that "some of the councils are extremely well informed and, in some cases, they are actually active participants" in AV trials. However, Participant ɑ did note that most of the councils that they had observed who are engaged in AV trials were urban-based planning councils. Participant ε thinks this is the way to get the CAEV implementation processes underway and that highway and transport planners in particular are "already on board" because they are "already thinking of 20, 30 years [ahead]" and "that's how [they] operate". However, "planning authorities are often a bit slower".

With industry, rural CAEV implementation primarily depends on business case, markets and profitability, with economics being a key challenge group discussed by the interview participants. This is discussed later in this chapter.

> *"[Industry needs] continuous improvement in technology and by making [CAEV technologies] more accessible and affordable you're improving your economic case and business case."*

Participant β

To help achieve this, Participant β then suggested that the government needed to work with industry and subsidise them until the balanced is reached. Participant β explained that the challenge for government in particular was around certification to allow industry and planning authorities to implement CAEVs and their technologies. Participant ɑ explained that there are government certification agencies, of which "the DfT is part of informing that process", that "see systems… go through approval and certification processes". However, Participant ɑ believed that "a lot of those processes don't really exist" for CAEV technology. This meant that "these certification agencies need time to [develop] a different set of skills within them to actually do the certification of a very different system" to what they are used to.

Participant β summarises the institutional challenges in the UK and cited the German Fraunhofer Society as an example which consists of "large industrialisation centres" that bridge the gap between university research and industrial manufacturing:

> *"Compared to other industrialised nations, as a country (UK) we suffer from technology translation. One thing that the government can do to accelerate [the development and implementation of CAEVs and their technologies] is create a translation centre… to cover some of that ground [of technology translation]."*

Participant β

Technological

Technological challenges were split into two main groups of discussion. Firstly, on-board technologies, which included all the technologies within the vehicle including all hardware and software. As already discussed, the rural environment in which a CAEV must operate is extremely challenging. Participant α suggested a need for rural CAEVs "to concentrate solely on what's available on the vehicle". Participant δ supported this citing that CAEV companies "would rather the vehicles were as self-contained as possible". Keeping operations internal helps to avoid "cybersecurity issues" (Participant α, Participant δ) and reduces the need to upgrade or instal infrastructure in rural areas which has already been described as a potential challenge. In terms of high-level automation such as those of SAE Levels 4 and 5, Participant α believed that there was still "a lot of uncertainty around when you're actually going to see those levels of automation" particularly in challenging rural environments.

"Jumping to level five … has to be a significant time away from now. If you look back at the predictions that were made five years ago, we haven't made five years of progress at all."

Participant α

Secondly, they highlighted the technological challenges of CAEV testing, particularly in rural areas. Participant α referred to simulation and test-track trials which were "gradually solving problems" however they didn't believe that "anyone has really worked out how to do the [real-world] testing properly". Participant δ believed that real-world testing is justifiable, particularly in the rural case, to "learn about edge-cases so that they can go into programming and minimise the likelihood of problems further down the line". By "edge-cases", Participant δ referred to challenging "situations that are rare but will cause a lot of problems for an autonomous vehicle". Participant γ explained that rural policy makers are beginning to see the potential of rural CAEV testing but they're not getting anyone "knocking on their door [asking if they] can run a pilot". However, Participant γ believes that policy makers "probably should be [running pilots] because [rural roads] are probably a safe place to do a trial if you can do it on a small scale". In this case, Participant γ believed that the "interface between the technology, the investors and innovators and the rural [is] the biggest barrier" to rural CAEV implementation and is defined by the level of testing. Explaining the lack of interest in trialling rural public transport services, Participant α described a "vicious cycle" in which individuals living in "patchy, underserved" rural areas were forced to "invest in [their own] private car" which further decreases demand for already limited public transport services.

Economic

It appeared to be difficult for the participants to economically justify rural CAEV implementation for a number of reasons, mainly the lack of business case and investment due to sparse and often poorer populations. "You don't tend to see many rural applications… because the business case is much harder … to achieve" (Participant α) due to the "right volumes [required] for economic principles" (Participant β). Participant ε suggested that it came down to "price, product, speed and efficiency", which are better served from a business point of view in urban scenarios.

Further economic challenges include the threat of automation on jobs, particularly in typically lower-skilled rural areas (Participant α, Participant ε). Further, government, local authority and industrial investment is lacking which discourages rural CAEV implementation and testing (Participant α, Participant β, Participant γ). And finally, the initial user cost of using CAEVs, as Participant ε warned, may be "so excessive … that it's going to impact [CAEV] service[s] moving forward".

Social

It was suggested that defining the target user type for CAEV services could be difficult in rural areas. There are a range of potential users all requiring access to different facilities and destinations. Participant γ described the need for rural people to access "good [local] jobs" and "cultural attractions" whilst they envisioned "commuting stretched over a long distance because it happens less often" due to emerging and unpredictable working from home and co-working patterns. Participant δ anticipated a complex design challenge in terms of CAEV users with "younger people and business-oriented people" as the most likely "early adopters" of CAEV technologies but that these types of services "will ultimately be for people more at the margins, so the older people [and] those people with particular impairments".

Another well-discussed social challenge was that of the user's perception of CAEVs and new technologies in general. Participant β suspected that people "will always tell you … that the technology costs too much, it is not as reliable as they would like [and] it's not as efficient as they would like". Further, "the willingness to accept the technology could be an issue". Participant ε described potential "luddites" and that a challenge is people's "perception of safety" with regards to new technology. In particular, rural areas will "probably have a lot more vocal communities for trying to reject things, because they're not liking change" (Participant δ).

In relation to perception is practical ability for users to use new technologies. For example, Participant γ envisaged a problem with the potential "need for people to have smartphone-enabled technologies for booking tickets, for checking into the vehicle … for micro payments" both in terms of rural demographics but also referring back to the patchy nature of internet coverage. Participant δ agreed by noting "if the technology totally depends on a phone-centric interface … then that's going to completely discount many people" including those that lose or break their phone. Both perception and technology use challenges were seen as greater challenges in the rural context.

4.4.4 Rural CAEV Implementation Benefits

Although challenges were the most discussed theme that emerged from the interviews, there was significant discussion around the potential benefits of rural CAEV implementation for rural areas and communities. These benefits were grouped into the sub-themes described in this section which are in descending order of most references.

Business Case

With CAEVs there is no "labour directly involved in operating the vehicles… so automation gives you the opportunity to have much larger fleets of much smaller vehicles" (Participant α). This was identified as a particular advantage in rural areas where currently there are "bus service[s] where you've got a 20-seater or a 50-seater and you're ending up with occupancies of 1 or 2 people" which is "not an economically sensible solution". Participant α went on to suggest such an automated service would be well suited to on-demand services where "you are reducing the labour cost and the variable costs per mile that aren't fixed". Participant β added that automated services can run for 24 hours with the advantage "that you can work at night [for] better productivity in theory". Participants γ and ε discussed similar advantages but for the business case of delivery services.

Additional general business case CAEV benefits included the scaling of software which is “a fixed cost once you’ve got the software for the autonomy working” (Participant α) as well as off-road delivery capabilities (Participant ε) which could be particularly advantageous in rural environments.

Social

The flexibility of CAEVs on-demand to serve rural societies was discussed by four of the five participants. Participant γ described a family situation in which there are multiple destinations for each member to be delivered to and Participant δ described less able people with varying weekly tasks all being supported by an on-demand CAEV service.

Economic

Relating to the previous business case benefits, Participant α suggested that CAEVs would reduce labour costs, variable costs, and the relative cost-effectiveness of scaling up software across entire fleets. Participant β described the potential high initial costs of setting up a CAEV service, but with automated charging and connected infrastructure there was potential to “leave an autonomous vehicle … working for months or years without intervention”. Participant γ also argued that, despite what some critics of automation might believe, a better connected and automated transport network would be able to generate “footfall in the rural place and actually that’s an opportunity for local businesses to … be connected”.

Specific rural benefits

Despite the current transport dangers on rural roads, Participant β noted that “the great thing about rural environments … is that there aren’t dense populations so in a way it is great from a safety point of view” and went on to describe the opportunities for delivery applications such as drone and pavement-sharing vehicles which could be more dangerous in busy cities. Participant ε identified an opportunity for CAEVs to make use of rural off-road trails and public rights of way which they described as “fantastic routes that have got thousands of years of history of connectivity and they were made to connect these villages up together in the straightest route that you could”.

Technology

Participant δ believed that CAEV testing and implementation in rural areas would aid the development of CAEV and positioning technologies. CAEVs encountering particularly rural issues such as “spaces that don’t have white lines” and “dealing with potholes” would make “each generation of updates in the vehicle or software” more capable. Participant ε made a similar point referencing their off-road rights of way concept and CAEVs developing technologically to deal with using these alternative rural routes.

Agriculture

Both Participants β and ε recognised the benefits CAEV technologies could bring to the agriculture sector, and both cited the use of unmanned aerial vehicles (UAV) for pesticides (Participant β) or monitoring livestock and land use (Participant ε).

Environment

Comments on CAEV benefits to the health of the environment were limited. However, Participant ε commented that “on the whole [the implementation of CAEVs] would be a boom for environmental progress and sustainability”.

4.4.5 Rural CAEV Applications

The next identified theme was that of CAEV *applications* which encompassed discussion around how and in what form CAEVs could be implemented in rural areas and communities. Many of the following applications tied into the *benefits* sub-themes identified.

Rural Transport Hubs

Both Participants γ and ε discussed transport hubs in detail and were familiar with the concept (see section 2.5). Participant γ described the concept as a "level of the hierarchy of mobility" where rural hubs were connected to urban centres through major transport links (major roads or rail links for example) and connected to their sparse rural communities through smaller, possibly autonomous transport networks. The hubs themselves would act as "district centres" with community spaces and activity (Participant ε). Both participants suggested these hubs could be used for delivery storage and distribution using CAEVs and UAVs to distribute goods to the surrounding rural region. Participant γ "can see [hubs] springing up more in the countryside" complimented by CAEVs and as co-working spaces.

UAVs and Drones

Four participants recognised the opportunity and benefits of rural UAV applications, the agricultural and delivery potential of which has already been discussed. Similar technologies are needed to support UAVs as CAEVs, such as connectivity and energy infrastructure. Both Participant γ and ε could imagine "drone platforms on roofs" of key infrastructures which could be used for multiple applications including "drone delivery", "agriculture", "flying doctors", and "police and security" applications.

Public Transport Services

Participant α commented that "a few companies have had a look at trying to … bring on-demand or fleets of taxis that you ride-share" (Participant δ also discussed the opportunity of "robo-taxis") but admits that they "haven't seen anyone come up with a perfect solution". Despite this Participant γ explained that planners are "interested in things like mobility as a service, they were interested in car-share, car-pooling, active transport, getting more people on bikes, more people walking, better ways of connecting between modes of transport that are more sustainable", however these may not necessarily involve CAEVs. Participant γ did however note that "we'd love to see driverless trains" and that people "still like buses" and CAEV technologies had the potential to "make buses better".

Other Applications

Agriculture was a widely discussed and specifically rural application of CAEV and associated UAV technologies for a variety of applications within the agriculture banner. Also mentioned were freight deliveries and the use of vans either controlled or supported by CAEV technology. Finally, there was brief discussion of opportunities for rural trials to aid the development of "more widespread, more affordable, more efficient [and] more reliable" CAEV technologies (Participant β).

4.4.6 Urban Prominence

Urban-related CAEV discussion often took place throughout the interviews. Typically, these were in relation to urban case studies that the participants were referring to as they were often unable to recall specifically rural examples. Participant ɑ begin their interview acknowledging the lack of rural CAEV projects they had come across. In terms of practical demonstrations and trials, Participant ɑ went on to say that they "haven't heard of a project with rural as a focus".

> *"When I saw this interview was announced I had to look back and try to think which of our CAV projects have had a rural flavour and I was quite taken by how few of them actually had."*

Participant ɑ

Both Participants ɑ and δ believed that rural areas would be the last to see CAEV technologies after urban areas, motorways and major roads. Both provided reasoning for these assumptions. Participant ɑ noted that the "urban [environment] is easy [to implement CAEVs] because it's slow and, although it's a really messy complex environment, at least if something goes wrong you've got time to react, and the consequences are quite low". Participant δ described "simpler" motorway scenarios with "the traffic all on the same side, all going in the same direction, nice lane markings [and] no pedestrians to deal with". As Participant ɑ described, these types of scenarios are the opposite of the urban environment, adding that motorways and major roads have "very well maintained" infrastructure. They then described rural environments as "the worst of both of those".

> *"You've got a complicated environment to operate in perhaps not even with a white line in the middle, maybe 120mph speed onwards compared to the vehicle passing you, so you've got all the negatives all at once".*

Participant ɑ

Participant ε described how CAEVs often feature in conversations about "smart cities" and "15, 20-minute cities" but questioned how we can make "15-minute [rural] communities". Participant δ supposed that "in the developers minds if they can get things working in urban environments then that should still be the same for rural environments in terms of the technology development side of it". They also noted that urban planners are starting to understand the needs behind CAEV implementation but "there may well be certain issues in rural areas that won't be picked up by a focus on urban areas".

4.4.7 Perspectives on Hypothesis Proposal

The third topic of discussion across the interviews was that of this thesis' project proposal. The proposal of a rural-based CAEV index was described and the participants were asked to comment on the proposal. Overall, the reaction to the proposal was positive, with participants noting the lack of work done in rural areas and the need to build awareness and develop guidance for transport planners.

Seeing how few rural CAEV projects they could find prior to interview Participant ɑ acknowledged that this area of research needed addressing. They believed that such a project was "very timely" and that "as a whole there's a gap at the moment in advice and guidance for local authorities and transport planners in particular". However, they were uncertain how to precisely fill the gap, but suggested that "it probably starts off with some sensible research".

Participant γ added that there is a "very simple step of awareness raising of what is likely to happen in the next 3, 5 and 10 years and longer". They went on to say that the challenge would be to "firstly break [the technology] down into things that are realistic for a rural area, and secondly, as I think you're doing, warning them of the threat of if all the cities are going to be doing autonomous delivery of products and banning all petrol cars … the rural has to ensure that the people living there are not going to hit this brick wall when trying to get into a city." To summarise, Participant γ suggested that to see progress in this area there needed to be "simple awareness raising and framing [CAEV implementation] as an opportunity rather than … as challenges they will have to deal with".

Participant δ noted that a challenge of the research would be to consider "all the different sorts of people that have a say on the rural community", but that the project sounded like "a really good thing to do" and that "it'll be interesting".

Participant ε felt that the work of this project needed "looking into … because all of these applications need to be converted into function and usability". They felt that there was a need to "humanise" this area of work. Participant ε also suggested considering "transference [of the index] to other areas" citing poorer nations with more extreme rural environments than the UK.

4.5 Discussion and Conclusions

This section combines the results of the survey and interview analyses and discusses the implications of the results on the research questions outlined in this chapter, research hypothesis and the CARTI proposal.

4.5.1 Discussion of Research Question A

To what extent is the implementation of rural CAEV technology currently a priority for transport planning professionals?

To summarise the survey results from Q7 to Q9, rural transport planning is, in general, a lower priority than urban transport planning. To support this, there were a clear lack of rural examples discussed in the interviews with participants repeatedly referring to urban examples of CAEV implementation and technology applications. The survey revealed that within the context of this urban bias, modern transport technologies were *rarely considered* in rural transport planning, with specifically CAEVs only *sometimes considered* in 15% of cases. The implementation of rural CAEV technology was only rarely a consideration. Communications infrastructure and automation, fundamental aspects of CAEVs, were ranked the least important priority areas in the survey. Both interview Participants α and δ believed that rural areas would be the last to see CAEV technologies and suggested that rural CAEV implementation will not be a priority until the technology is proven in other less complex environments.

4.5.2 Discussion of Research Question B

To what extent do rural transport planners believe that CAEVs are an important factor for the consideration of future sustainable transport solutions?

Transport planners were cautiously optimistic about the benefits of rural CAEV implementation but did not yet see CAEVs as a priority or important element of rural transport, at least in the short term. The responses to survey Q13 however, suggested that there was some foreseen potential amongst transport planners for rural CAEVs, but that there was great uncertainty about if and when this potential would be realised.

The interview analysis supported these findings with participants highlighting multiple specifically rural benefits to implementing CAEVs. Participant α described a "vicious cycle" of current rural public transport services but all participants could envisage a future where these current rural transport service challenges are to some extent solved by CAEV implementation.

In terms of sustainable transport solutions CAEVs were overall considered a sustainable solution. However, both the survey and interview results highlighted concerns over economic cost, most clearly highlighted by Figure 4.7. In the interviews, it was the initial costs of the implementation that was identified as a concern, but these were expected with any new technology and were assumed to reduce as business cases improved and CAEV use increased. Given the electric aspect of CAEVs, environment quality was expected to improve. Although barely discussed in the interviews, there was a sense that the benefits of electrification were already well known and therefore did not require explicit discussion. What was clear across both survey and interview results was that the social pillar of sustainability was expected to benefit the most from CAEV implementation.

4.5.3 Discussion of Research Question C

To what extent do rural transport planners understand CAEV technologies and their infrastructural requirements?

The elicitations identified a range of options that were available regarding raising awareness and understanding of CAEV planning requirements. The survey responses appeared to be split into suggestions that aimed to raise awareness, and suggestions seeking to aid understanding. There was a sense among the responses that if the technology or ideas didn't work or couldn't be proved safe of effective to a great enough extent, then the planning profession would ignore them. Therefore, to spread awareness, CAEV technology must work to be worth a planner's time. One survey respondent suggested that:

> *"…transport planners are interested [in understanding CAEVs] but are under pressure due to budget reductions so don't have time for the training, CPD or headspace to think of new ideas; so [interventions] have to be time efficient."*

This was echoed amongst interview participants, who explained the pressures planners are under given their relatively small teams and vast range of responsibilities. They expressed a clear need for improved awareness not only amongst transport planners but the wider networks they work with, including government and industrial institutions. A strong communicative relationship between these players was identified as one of the biggest challenges facing CAEV implementation. In relation to this was a lack of understanding of the technology, but also uncertainty around the business case and real-world applications of CAEVs.

Ultimately confusion and uncertainty regarding the requirements for rural CAEV implementation were identified with a wide range of survey responses to Q11 and respondents explicitly admitting their industry had little to no understanding of CAEVs. There were however options provided to counter this lack of understanding as shown in the results from Q15, and the range of suggestions offered implied a willingness for transport planners to engage with CAEV awareness and education, dependent on factors including relevance and time. This was echoed by the interview participants, who could see the overall potential of CAEVs but were unsure how to break through the awareness and understanding barrier to get to the implementation stages.

4.5.4 Conclusions

Overall, the responses to the elicitations indicated that the thoughts of the professional rural transport planning industry generally aligned with the findings in this thesis, primarily that priority areas for rural transport are those of accessibility, yet not of technology. The results reiterated the lack of technological transport systems and rare consideration of CAEVs in specifically rural scenarios. The depth and breadth of the challenges to and potential for rural CAEV implementation adds to the understanding of this issue. Whilst transport planners recognised the major rural transport needs, as identified in this thesis, they did not necessarily identify CAEVs as a potential solution without being prompted. Despite this, they did recognise that CAEV technologies may be able to provide some of the benefits highlighted, but a greater awareness and understanding would be needed before progress in this area could be made.

Through the elicitation exercises described in this chapter, the extent to which CAEV technologies are currently a consideration and priority for rural transport planning professionals was identified. Further identification of the extent to which transport planning professionals, and wider institutions, understand CAEV technologies and their infrastructural requirements has been achieved. In addition, additional requirements that are needed to aid rural CAEV implementation have been identified, the most conspicuous being the engagement with and between institutions developing, regulating and implementing transport technologies.

The hypothesis introduced at the start of this chapter, that a lack of specifically rural implementation research and trials meant that transport planners were likely to be ill-informed and uncertain of both the potential of CAEVs and their implementation requirements, was explored through elicitations with transport planning professionals. To an extent, this hypothesis has been found to be true; understanding of CAEV potential to alleviate rural transport challenges, notably accessibility, was lacking and the challenges facing implementation were found to be diverse and non-specific. Consequently, the remaining chapters of this thesis describe the development of the CARTI as a tool to aid transport planner understanding of CAEV's, their technologies and infrastructure requirements.

The reaction to this proposal was positive across both elicitation types. The survey results highlighted the potential usefulness of such a proposal, whilst the interviews referred to the timeliness of promoting and developing CAEV implementation guidance for planners. In both cases there was reference to a need for a simple initial solution to bring together the complexities of CAEVs in a way that would be presentable and understandable for transport planners, given their workloads and responsibilities. Therefore, the following chapter progresses to develop the CAEV Rural Transport Index (CARTI) to support transport planners in CAEV decision-making and implementation.

5 THE CAEV RURAL TRANSPORT INDEX

This thesis has identified a need to highlight the requirements for CAEV technologies to operate in rural areas and on rural roads in the UK. This is so that today's transport planning professionals, who are responsible for present and future transportation systems, are equipped to understand, plan for and develop modern rural transportation infrastructure and strategies. Any hard infrastructure projects must be cost effective as they have typical design lives of at least 50 years. However, the rapid development of technology, including that of CAEVs, will require integration with hard infrastructure. As such, there is a need to understand future technologies now, so that systems and strategies can be implemented to create future-ready transport environments.

To meet this requirement, this chapter describes the development of the CAEV Rural Transport Index (CARTI). This index was designed to be used to identify the levels of need, capacity and overall potential of different rural areas in terms of CAEV-related transport implementation. The CARTI is based on the literature reviews conducted in the earlier chapters of this thesis. These identified relationships between the needs of rural communities and poor rural transportation development with the potential benefits of CAEVs and their associated technologies.

Whilst useful, free and accessible government data is expansive and fragmented. Transport planners do not have the resource to search through data, decide the relevant datasets and then explore methodologies to be able to apply them. Therefore, there is a need for simple tools for transport planners to assist in the exploration and implementation of rural transport solutions such as the proposed CARTI.

Existing solutions and indexes that attempt to address similar issues fall short of the CARTI solution. Typically, sustainable transport indexes that support transport planner decision making focus solely on urban sustainable transport solutions (Regmi and Gudmunsson, 2017, Zito and Salvo, 2011). In other cases, solutions do not explicitly address rural transport development, rather targeting rural development more generally and within the social sphere (Abreu et al., 2019, Caldwell et al., 2015, Kim and Yang, 2016, Michalek and Zarnekow, 2012a, Ramani, 2018). In addition, rather than explore emerging technologies, a number of solutions in the literature attempt to apply existing transport solutions to rural transport problems, as highlighted earlier in this thesis by the UK government's urban mobility strategy (Vitale Brovarone and Cotella, 2020, DfT, 2019a, Workman and McPherson, 2021). The solutions inclusive of emerging technologies, such as CAEVs, only tend to provide a general overview of possible solutions without measurable elements that target specific actions or cannot be applied at local rural scales (KPMG, 2020, Lcas et al., 2019, Midlands Connect, 2020b, RTPI, 2021b, Sustainable Mobility for All, 2019).

There are however existing studies that have similar objectives, but produce or suggest alternative solutions, to the CARTI (Dianin et al., 2021, Slee, 2019, Zhang, 2019). Details from these studies were very useful in informing the CARTI's development.

This chapter therefore proposes a unique methodology that links the measurement domains of transportation development, rural development and technological development together into a single future transport measurement index at the local level. The CARTI is presented as a simple yet novel solution to aid transport planner understanding of rural CAEV requirements and accelerate rural CAEV implementation. The CARTI also forms a baseline from which further studies can develop future transport technology indexes to contribute to CAEV solutions across the UK and globally.

5.1 The Purpose of a Transport Index

An index is a collection of indicators (measurements, parameters, or variables) identified to be significant for a particular sector of development (Roberts et al., 2006). Strategies that use a selection of indicators covering a broad range of multidimensional issues within a particular development sector are more likely to yield sustainable outcomes, as opposed to those using single instruments (Ramani, 2018, Zito and Salvo, 2011). An index can be used to identify priorities for development and assess contributions towards that development. An index can also be used to inform policies and strategies to aid equal development distribution among populations (Roberts et al., 2006). Incorporation of spatial indicators into planning and policy processes is useful, especially when the selected indicators are understandable (Cheng et al., 2007). Sustainability also plays a large part in the development of any index and is therefore a key consideration throughout the index methodology.

In this case, the CARTI aims to equally distribute transportation development opportunity among rural populations and to start to bridge the technological transportation development gap with urban populations. As a policy analysis tool, an index that can be applied across regions for comparison and equity purposes is highly desirable (Michalek and Zarnekow, 2012b). This is a particularly important function of an index when considering applications across rural regions, which have been shown to be lacking in many development areas including transportation. Indicators are able to capture the multidimensionality of sustainable transport and break down concepts into management units for comparison, benchmarking and communication (Castillo and Pitfield, 2010).

5.2 CARTI Themes

In the case of the CARTI, the development sectors of interest are those of rural development and transportation development. There is an abundance of existing literature for both these development domains, which includes research into developing indexes to measure and assess them. Rural development index research primarily focuses on societal development using measures relating to health and personal wealth. On the other hand, transportation development index research often takes a large-scale approach, often exploring nationwide transportation development. Any smaller analyses focus on the development of urban, or inter-urban, transportation systems, rather than rural systems.

It is rare to find explicit research that unifies these two domains, with rural development index research rarely focusing on transport and transport development indexes primarily focused on urban systems. This highlights a gap in the research and the contribution to knowledge that can be made by the CARTI and the related research in this thesis.

The CARTI therefore measures the need and capacity of transportation systems for specifically rural areas, with a focus on modern transportation technologies, which is an additional uncommon theme in the index development literature. As identified, CAEV technologies have the potential to bring specific benefits to rural communities across the sustainability spectrum. Through the development of the CARTI, rural transport challenges can be specifically addressed through the ways in which CAEVs and their technologies could be implemented.

5.3 Dual-CARTI Approach

The CARTI, whilst providing a standalone indication of rural CAEV potential, consists of two distinct elements. The first determines whether a rural community has a need for CAEV technology, and which factors influence this need. This needs-based element identifies the present transportation challenges facing a specific rural area and highlights areas that CAEV technologies are designed to improve. The second determines the capacity of a rural area to be able to integrate CAEVs and their technologies so that they can serve and meet the determined developmental needs of their rural communities. A collection of indicators that highlight capacity in this way has aided the identification of potential approaches for CAEV adoption and to what extent adoption is currently possible.

Through the analysis of existing rural and transport development indicators and indexes, a natural split between indicators that are capable of measuring capacity and need was identified. However, there remained some instances where indicators could be used to measure both. This finding aligns with the theory that, broadly, there are two types of development index. Firstly, there are those which measure existing condition quality, known as 'result' indicators, and secondly, there are those that evaluate the extent of development, known as 'cause' indicators (Kim and Yang, 2016). Primarily in rural social-science studies, capacity–needs assessments exist for the purpose of identifying gaps in development based on the needs of communities, where a need is considered as a gap between current conditions and required conditions essential for change (Muller et al., 2008, Stephen and Triraganon, 2009). Whilst the terms 'cause' and 'result' suggest a way of measuring the beginning and end of a development process, development should be a continuous process. The separation of these indicator types creates a space for a 'result' index to measure current levels of development (need), and a 'cause' index to evaluate development progress (capacity) (Kim and Yang, 2016), or, more specifically, the gaps in development that need bridging.

Therefore, the development of a dual-CARTI was pursued, with one element assessing the level of need that a rural area might have for CAEV technologies and the other measuring the capacity of a rural area to be able to implement CAEVs.

5.4 CARTI Development Methodology

The foundation of the CARTI methodology was based on the combination of two existing methodologies.

Firstly, the Evaluative and Logical Approach to Sustainable Transport Indicator Compilation (ELASTIC) attempts to aid the identification and selection of sustainable transport indicators (Castillo and Pitfield, 2010). ELASTIC was developed as a systematic approach to indicator selection to support transport planning and is therefore a relevant method to develop the CARTI. No indicator set will perfectly represent a complex system, but the selection process can be improved by defining methodological processes and assessment criteria. Defining these processes also improves the transparency and consistency of selection and therefore the credibility of the research (Castillo and Pitfield, 2010).

Secondly, Multi-Criteria Decision Aid methods (MCDA) use multiple criteria to account for the multidimensionality of decision problems, most often related to sustainability, and are often used to develop indexes consisting of multiple indicators (De Toro et al., 2004). MCDA methods vary in the way they operationalise the index indicators but most are based on linear weighted sum models (Hansen and Devlin, 2019). These simple models are almost universally more accurate than the intuitive judgements of decision makers (Kahneman, 2011). The MCDA process was used to develop the CARTI by combining the selected indicators, based on the ELASTIC method, into a single decision-aiding index.

The CARTI methodology combines the domains of rural development and transport development through an extended literature review of these domains and existing indicators, together with the experience of the authors in this field and elements of both the ELASTIC (Castillo and Pitfield, 2010) and MCDA (Hansen and Devlin, 2019) methodologies. The stages and steps of the CARTI methodology are described in Table 1.

In addition to the methodological structure, reference to existing literature has been made throughout this chapter to support the proposed methodology and aid decision-making within the methodological steps. This literature was used to determine how best to construct the CARTI in relation to rural transportation and future transport technologies.

5.4.1 CARTI Method

Table 5.1 summarises the method used to develop the CARTI, highlighting relationships to ELASTIC and MCDA processes which are complimentary. The stages and steps defined in Table 5.1 are indicated in the headers of the sub-sections in this thesis chapter.

Table 5.1 CARTI development methodology

Stage	Step	Step Description	Based On	Outputs
1 Defining Index Goals	i	Structure decision problem based on research aims and identified development domains	MCDA (1)	Results inform steps ii and iii
	ii	Define CARTI goals and need/capacity element requirements	ELASTIC (2)	Index Goals 1, 2a, 2b, 2c, 3 and index requirements
2 Indicator Selection	iii	Assemble collection of indicators from existing literature relevant to Stage 1 problem identification and goals	ELASTIC (1) MCDA (2)	202 existing indicators, their measurement methods and original sources
	iv	Consolidate indicator collection • Remove irrelevant indicators • Group similar indicators • Review relevant indexes	ELASTIC (4) MCDA (2)	38 consolidated indicator groups
	v	Determine indicator evaluation criteria including quality and measurement requirements	ELASTIC (4) MCDA (2)	Quality criteria
	vi	Select initial index indicators	ELASTIC (5) MCDA (2)	6 indicators (3 for each element)
	vii	Evaluate indicator quality and measurement performance	ELASTIC (4) MCDA (3)	6 indicators with absolute measurement values
3 Index Construction	viii	Determine scoring method to convert indicator measurements to comparative scores	MCDA (4)	Contributes to output x
	ix	Determine indicator weighting procedure	MCDA (5)	Contributes to output x
	x	Apply scores and weights to rank indicators and determine element and index scores	MCDA (6)	6 indicators with relative scores between 0 and 100
	xi	Assess the ability of the index to support decision-making	MCDA (7)	Case studies and evaluation

Step 3 of the ELASTIC method requires the contribution of stakeholders to themselves assess a selection of indicators and, using their expert knowledge, judge them based on their relevance and validity with respect to the type of index being created. In the case of the CARTI development method, stakeholders were engaged post index development. However, professionals were engaged in the investigations of Chapter 4 where ideas for the types of indicators that would be useful were established. Further, simple MCDA models, with which the ELASTIC method is combined here, are almost universally more accurate than the intuitive judgements of decision makers (Kahneman, 2011), further justifying the decision not to engage stakeholders mid-methodology.

5.4.2 ELASTIC and MCDA Methods

No indicator set will perfectly represent a complex system, but the selection process can be improved by defining methodological processes and assessment criteria. Defining these processes also improves the transparency and consistency of selection and therefore the credibility of the research (Castillo and Pitfield, 2010). The ELASTIC process consists of 5 stages as outlined in Table 5.2. These phases contribute to the methodological framework described in Table 5.1.

Table 5.2 ELASTIC methodology (based on Castillo and Pitfield, 2010: page 6)

#	Stage	Action
1	Assembling indicators	Collect a long list of potential sustainable transport indicators.
2	Defining goals	Define the goal and sub-goals of the assessment.
3	Stakeholder participation	Engage with stakeholders and elicit their values and judgements.
4	Indicator evaluation	Systematically evaluate and select preliminary indicators.
5	Selection	Perform sensitivity analysis and select final indicators; derive transport sustainability profile.

Each MCDA step is described and then applied in relation to this study and the selected indicators. Although sequential, these steps can be performed simultaneously or iteratively (Hansen and Devlin, 2019):

1. Structuring the decision problem;
2. Specifying the criteria (indicators);
3. Measuring alternative's performance;
4. Scoring alternatives;
5. Weighting the indicators;
6. Applying scores and weights to rank indicators;
7. Supporting decision-making.

5.5 Defining Index Goals (stage 1, step i)

The definition of goals and sub-goals was needed to define the direction of the index so that relevant and precise indicators could be selected (Castillo and Pitfield, 2010). This was done by reviewing firstly the research aims and objectives described in this thesis, followed by a review of the research domains. This ensured that the indicator selection process comprehensively reflected the relevant characteristics of the research domains (Kim and Yang, 2016).

The research contained within this thesis aims to assess and enhance the potential of CAEVs to contribute to rural transport development (see Introduction). The CARTI serves to contribute to such a research aim, given that indexes are assessment tools often used to promote actionable policy or inform decision-making. To summarise the CARTI's purpose, it acts as a tool that assesses rural transport development needs whilst promoting the appropriate practical implementation of CAEV systems and technologies, thereby meeting, at least partially, each of these specific research objectives:

- Determine to what extent the needs of rural areas can be met by CAEV systems and technologies;
- Identify the practical challenges of CAEV implementation;
- Set out the requirements for rural CAEV implementation where there is a distinguishable need;
- Contribute to the rural implementation of CAEV systems and technologies.

The major research domains addressed by the CARTI are those of rural development and transport development. Through the creation of the CARTI, these domains were brought together and integrated with the potential of future transport technologies in rural scenarios. Whilst these major domains were consolidated in the CARTI, they are distinctly separate in the literature. Due to the lack of literature regarding rural CAEV development and implementation, finding indicators to assess the capacity of rural areas to support CAEV implementation was more difficult than finding needs-based indicators. This is where analysis of recent projects including KPMG's AVRI (Section 5.6.2) and FoRMS (Midlands Connect, 2020a) were useful to better understand the barriers to, and capacity of rural areas to support, CAEV implementation.

Considering the domain of rural development, there were three essential factors that were common across the literature (Kim and Yang, 2016):

- Using local people and government as the main development agents;
- Measurements must contribute towards improving quality of life and/or sustainable development;
- The primary domains typically relate to economy, education, environment, health and welling and culture and leisure.

These factors highlight that societal factors and social sustainability are important aspects of rural development. As an important social tool central to rural life, any measurement of transportation must reflect the society served and fundamentally seek to improve accessibility and improve quality of life. Whilst the economic and environmental aspects of sustainability are also adhered to in the CARTI, they continue to relate to rural society and contribute to quality of life.

Considering the domain of transport development, transport-related and environmental indicators were the most widely used to measure sustainable transportation, whereas economic measures were less commonly seen and socio-cultural indicators even less so (Jeon and Amekudzi, 2005). This suggested that there is a domain chasm between rural development domains, which look specifically at society, and transportation development domains where socio-cultural indicators are rare, despite the improvement in accessibility, a social problem, being a core objective of transport development (Cheng et al., 2007). However, these transport-related indicators included safety indicators, which largely focused on fatalities or injuries, and therefore could be argued to be directly related to the social domain given that high fatality rates could relate to quality of life.

Environmental indicators, on the other hand, were mostly linked to emissions and fuel consumption, which could also be viewed as economic indicators relating to efficiency and cost to the user. A set of key factors that influenced sustainable transportation development were identified, which appear to be more sustainably balanced than previous research (Zito and Salvo, 2011). These factors were technology, economic development, spatial and land-use patterns, government policy and social/behavioural trends. However, as with many studies, these factors were determined based on urban scenarios rather than rural. It remains that urban development is dominant in most of the index-based transportation literature (Cheng et al., 2007, Mahdinia et al., 2018, Nag et al., 2018, Perujo et al., 2009, Pregl et al., 2008, Ramani, 2018, Regmi and Gudmunsson, 2017, Zito and Salvo, 2011). Indexes and indicators across both rural development and transportation development sectors may underrepresent rural areas and their characteristics due to the urban bias behind the development of these indicators, the policymakers and politics behind them, as well as data collection and quality due to rural sparsity.

When developing the CARTI from a collection of existing indicators, the source and methodologies behind these indicators were examined to identify any potential urban bias and determine their relevance to specifically rural transportation development. The presence of urban bias itself further demonstrates a need for the creation of a rural-specific CARTI. Just as the CAEV requirements in urban areas are unique, so too are those in rural areas (Chapters 2 and 3). Due to the urban bias identified, the CARTI ensures that rurality is central to its function. No index specifically addressing connected, autonomous and electric rural transport development could be found.

Despite the emphasis of social factors in the rural development measurement literature, and the lack of them in the transport development literature, something sustainable, which both indexes across both domains strived to achieve, should be all-encompassing. Transportation does not have its own United Nation Sustainable Development Goal (SDG) yet plays a recurring role throughout the SDG collection (United Nations, 2021). As such, sustainable transportation must impact economic, environmental and societal wellbeing domains (Jeon and Amekudzi, 2005); otherwise, it does not serve its purpose. Given the importance of sustainability, particularly in the transport industry, it is clear from the literature that this should be the base upon which a collection of indicators is built (Castillo and Pitfield, 2010, Cheng et al., 2007, Litman, 2007, Sustainable Mobility for All, 2019). Further, sustainability is central to the ELASTIC methodology (Castillo and Pitfield, 2010), which references five objectives that must be addressed to ensure that transport development is sustainable, namely liveable streets and neighbourhoods, protection of the environment, equity and social inclusion, health and safety and support of a vibrant and efficient economy (May et al., 2001). Whilst these five objectives encompass each aspect of sustainability, there is an emphasis on ensuring social sustainability by using three social-centric objectives, and explicitly listing a single environment-based and a single economy-based objective.

Core to sustainability is domain equality, and the term “balance” is common across the literature and all stages of indicator selection, implementation and assessment processes. A balanced set of indicators reflects every aspect of sustainability at every level yet continues to reflect the required aims of the problem (Litman, 2007). Whilst the CARTI aims to address the social, environmental and economic domains of sustainability, there are additional domains specific to the rural transport and the CAEV development themes of this research. These additional domains are accessibility (inclusive of its physical, digital and financial components) and safety (inclusive of health and wellbeing). It is important that the CARTI recognises these domains in addition to those already covered in the literature, as it is these domains that actively bring together the previously unrelated domains of rural development and transport development.

5.5.1 Index Goals (step ii)

Based on the literature review findings in this chapter, Table 5.3 defines the CARTI's goals.

Table 5.3 Index goals and definitions

<table>
<tr><th>#</th><th>Goal</th><th colspan="2">Description</th></tr>
<tr><td>1</td><td>Contribute to research aim</td><td colspan="2">The index must act as a tool that assesses rural transport development needs whilst promoting the appropriate practical implementation of CAEV systems and technologies.</td></tr>
<tr><td rowspan="4">2</td><td rowspan="4">Address research domains</td><td colspan="2">The index must specifically account for domains relevant to CAEV-related rural transport development including:</td></tr>
<tr><td>a</td><td>rural development, transport development and the promotion of modern transport systems and technologies;</td></tr>
<tr><td>b</td><td>sustainability (social, environmental and economic);</td></tr>
<tr><td>c</td><td>accessibility (physical, digital and financial) and health, safety and wellbeing.</td></tr>
<tr><td>3</td><td>Be rural-centric</td><td colspan="2">The indicators themselves, or their method of measurement, must be rural-centric.</td></tr>
</table>

Expanding on these goals, the CARTI addresses the two different perspectives of the need and capacity dual-index approach. The needs-based element is the more traditional perspective in which the CARTI assesses the state of the defined domains in Table 5.3, and encourages action to improve the societal, environmental and economic state of the area being assessed. The capacity-based elements require an alternative perspective to assess the extent to which these domains have the capacity (or readiness) to adopt a given scenario, system or technology. As such, taking a dual-based index approach provided greater coverage of the domains that need to be addressed in Table 5.3. The main difference between the need and capacity goals is the consideration of environment (need) and infrastructure (capacity), which focuses on real-world implementation and the built-environment capacity to support CAEVs.

5.6 Indicator Selection (stage 2)

The selection of index indicators is not an exact science and methods vary across the literature. The method of indicator selection is often dependent on the person creating the index, the geographical application of the index and the extent of resources available to carry out the process. What is common is the theme of reviewing historic indicators in similar research or application areas and building on them. This method forms the basis for the selection of the CARTI's indicators. Therefore, a literature review of existing indexes was carried out to compile a list of existing indicators (secondary data) relating to rural development, transportation development and connected and autonomous vehicle and infrastructure development (Kaufmann et al., 2007, Michalek and Zarnekow, 2012b).

For example, a review of KPMG's AVRI (KPMG, 2020) found five relevant indicators based in the CARTI's domains and goals. These were:

- Number of EV charging stations—an understandable and relevant indicator for which data can be collected at multiple scales;

- 4G internet coverage—an understandable and relevant indicator for which data can be collected at multiple scales; this, combined with mobile connection speed (below), would provide a useful assessment of digital wireless communication capacity;

- Quality of roads—assessing generic road quality was identified as a good stepping stone to assessing machine-readable roads; however, it is difficult to measure this at the local level for accurate results as KPMG uses the World Economic Forum's (WEF) global competitiveness report, in which professionals provide their subjective opinion of the quality of their country's roads;

- Mobile connection speed—related to 4G coverage, but focuses on the speed, which will have to be relatively fast to support CAEVs, as previously discussed;

- Broadband—referring to fixed broadband, this indicator is less relevant, particularly as it is difficult to economically justify roadside wired communications infrastructure in remote and rural areas.

5.6.1 Assembling and Consolidating Indicators (step iii, iv)

In total, 202 indicators related to transport and rural development were collected from across the existing literature and indexes. From this indicator collection, indicators that were deemed irrelevant to the study based on the research aims and index goals were removed. For example, Average Monthly Earnings was irrelevant to transport development as it does not record the impact of income on transport use. In addition, it is irrelevant to rural development as it is not being used for comparison with urban environments, for example. A more useful indicator would be Proportion of Monthly Earnings Spent on Transport as it relates the earnings of rural populations to transport and accessibility. Similar indicators to this example remained in the refined collection.

The next step involved grouping similar indicators into indicator groups that represented the same or similar measurements. This process firstly further reduced the number of possible indicators to ensure that each indicator was distinct, and secondly established an idea of which types of indicators were the most common historically, related to transport and rural development. The top five most common indicator groups were found to be Emissions and Air Pollution, Road

Traffic Casualties, Access to Public Transport, Density of Infrastructure (Land Use) and Road Quality. At this stage, 38 distinct indicator groups were created, consisting of 148 individual existing indicators. Table 5.4 shows the five most common indicator groups.

Table 5.4 Five most common grouped indicators from the explored literature

Indicator Group	Frequency
Emissions and Air Pollution	27
Road Traffic Casualties	12
Access to Public Transport	12
Density of Infrastructure (Land Use)	11
Road Quality	8

As an example of this longlisting process, consider the indicator group *Vehicle Ownership*. This indicator group was made up of five existing indicators taken from different sources that all related to vehicle ownership. These were all typically used to suggest the numbers of private vehicles on the roads. Table 5.5 shows these specific indicators, describes them and the source they were extracted from.

As part of the indicator selection process, weights could have been used. In this case, *Emissions and Air Pollution* would have had the highest weight applied as it is the most frequent indicator used in the existing index literature. A typical weighting method in this type of scenario would have been to generate a factor based on the ratio of the frequency to the total number of indicators reviewed. In the case of *Emissions and Air Pollution*, this would be $\frac{27}{148}$, and the other indicators would have been weighted in a similar way. This could be used in conjunction with the proposed selection tests to generate a score for each reviewed indicator. The highest scoring indicators would then have been brought forward to be used for the index. However, the issue with weighting in this way is that CAEV application in rural areas is a relatively new study, and as such, historic indicators, even those taken from as recently as 5 years ago, have become less relevant. In addition, weighting historically frequent indicators would result in newer and more relevant indicators being lost. Therefore, weights were not applied to the indicators at this stage.

Table 5.5 Indicators within the *Vehicle Ownership* category

Indicator	Summary description	Index/Source
Registered Cars	Number of registered cars per 1000 population	Urban Transport Sustainability Index (Zito and Salvo, 2011)
Registered Vehicles	Number of registered vehicles in thousands	Sustainable Mobility Index – Sustainable Mobility for All
Shift from Road Transport	Measure of the shift from road to rail, water and public passenger transport	EU Sustainable Development Strategy - EC 2005
Vehicle Ownership	Motorized road vehicle ownership in rural/urban areas: private cars/motorcycles/bicycles	Performance Indicators for Transport - World Bank
Car Ownership	Private car ownership	Indicators to Assess Sustainability of Transport Activities (Pregl et al., 2008)

5.6.2 Indicator Evaluation Criteria (step v)

Once the indicators had been collected and grouped, the next stage was to evaluate these indicators. One of the methodological challenges of developing an index is the process of selecting a balanced set of objective and subjective indicators and the process of their evaluation (Abreu et al., 2019). In addition, the indicators selected need to have been theoretically robust, yet simple enough to be understandable and interactive for planning processes (Cheng et al., 2007). The CARTI’s indicator selection process therefore consisted of multiple stages. As such, the existing literature that attempted to set out these stages was reviewed, not suggesting which indicators to select, but detailing the processes of deciding how to select the required indicators using indicator quality criteria.

A review of well-received literature on the subject of indicator quality criteria took place. To help define a list of indicator quality criteria for the CARTI, the context of the research behind the CARTI’s development was also considered in terms of time, cost and computational capacity, as well as the aims and objectives of the research. These quality criteria were heavily influenced by the following works summarised in Table 5.6, Table 5.7 and from the ELASTIC method (Castillo and Pitfield, 2010) which defines five desirable indicator attributes as:

- Measurability;
- Ease of availability;
- Speed of availability;
- Interpretability;
- Transport impact is isolatable.

Table 5.6 Summary of indicator quality criteria (Litman, 2007: page 13)

Criteria	Description
Comprehensive	Indicators should be specific enough to the problem, but broad enough to collectively cover the entire extent of the problem.
Data quality	Users of the index must be able to collect index data that is of sufficient quality for the needs of the index otherwise the index becomes redundant.
Comparable	The indicators and data they require must be comparable both over time and geographically for progress and regional comparisons respectively.
Understandable	The indicators must be easy from all stakeholders to understand from planning professionals to local residents who may be impacted by any consequences of the index.
Accessible	The index and its results must be designed so it can be made easily accessible; preferably visualised and made available to all stakeholders.
Transparent	All aspects of the index should be made available to all stakeholders at all times; making the index understandable and accessible will aid transparency.
Cost effective	The implementation of the index must be economically sustainable.
Net effects	The index must be sustainable with all stakeholders benefiting as equally as possible.

Table 5.7 Rural development indicator quality criteria (Michalek and Zarnekow, 2012: page 13)

General evaluation criteria	
Efficiency	The index has to be cost efficient in its construction then compared to the outcomes it gives.
Effectiveness	The index has to measure what is intended to be measured.
Relevance	The index has to be relevant for policy objectives (i.e., fulfil the policy specific criteria summarised in the next column).
Sustainability	The index has to be useful in both the short and long term.
Sufficiency	The index has to be sufficient to answer the question of quality of life in evaluating the policy.

Policy specific criteria	
Regionality	It should be possible to calculate index at regional and local levels.
Rurality	The index has to be applicable for rural areas.
Frequency	The index has to make it possible to calculate the frequency in line with the programme's requirements.
Objectivity	The index has to be derived with minimum subjectivity.
Transparency	The way of derivation of the index has to be clear enough for other researchers to replicate.
Simplicity	The index has to be easily understood by policy makers and public.
Comparability	The index has to be comparable across regions and countries.
Dynamics	Since the index has to measure changes over time it has to be dynamic.

Table 5.8 describes the CARTI indicator the quality criteria to select the indicators.

Table 5.8 CARTI indicator quality criteria

Quality Criteria	Description
Availability	The data required to measure the indicator must be easily and freely available in a usable format. The increased availability of modern data has made it possible to better assess specifically rural attributes (Michalek and Zarnekow, 2012b), although the availability of rural-centric data remains less than equivalent urban-centric data.
Measurability	The indicator must be able to be easily measured given the available data. Indicators must also be able to be measured across a range of rural scenarios and locations, therefore ensuring comparability. This is an important attribute to consider particularly as this is an attempt at a rural-centric index. Given the extent of rurality, it is desirable that such an index is capable of application across a range of rural areas with little adaptation (Abreu et al., 2019).
Reliability	Whilst still available and measurable, the data must also reliable so that the results are verifiable and cannot be contested. Credibility and data quality are vital aspects to index development (Kim and Yang, 2016).
Understandability	The data must be easy for any stakeholder to understand, particularly transport planning professionals, ideally in both raw and modelled formats. The criteria of transparency and interpretability are also included within this attribute. The use of the indicators within the context of the index must also be understandable. Where indicators have been brought together for a specific purpose (i.e., to build an index to support the aims and objectives of a research project) these should not be used outside of this context (Castillo and Pitfield, 2010, Jeon and Amekudzi, 2005). Therefore, it is important that the individual indicators themselves as well as the broader index context are understood.
Effectiveness	The data and indicators must perform their intended functions in relation to the research aims and objectives. Considering the aims and objectives of this research an effectively performing indicator must encompass the themes throughout this research including those of sustainable, transport and rural development. Further, the selected indicators must be effectively independent and not result in the duplicate measurement of aspects (Kim and Yang, 2016), similar to ELASTIC's requirement of isolatable impact (Castillo and Pitfield, 2010).

5.6.3 Number of Indicators

The number of indicators that make up an index varies across the literature. Whilst a comprehensive set of indicators may aim to result in a broad and detailed assessment of an issue, they require extensive collection and consistent levels of data quality across all indicators. An index with a limited number of indicators where quality data are readily available and easy to collect may, on the other hand, lack meaning and depth in trying to address an issue. If fewer indicators are used, fewer aspects of the issue can be captured in that index. This may undermine the purpose of an index to bring together a selection of related indicators to aid the solution to a multi-dimensional problem. Although there is no recommended number of indicators amongst the literature, it is suggested that a balance is found between a limited set of indicators that are easy to collect and a comprehensive set requiring excessive collection (Zito and Salvo, 2011). A range of numbers of indicators was found in the literature, ranging from 55 split into five separate themes (Pregl et al., 2008) to eight (Regmi and Gudmunsson, 2017), dependent on geographical scale and data availability and quality. The basis upon which this index selects it's number of indicators aligns with the findings that an index should comprise a collection of indicators as small as possible (Castillo and Pitfield, 2010).

5.6.4 Indicator Selection (step vi)

The selected indicators based on the selection methodology met the index goals defined in Table 5.3 to a sufficient extent. Specifically, the selected indicators contributed to goals 1, 2a and 3 whilst each meeting at least one element of both goal 2b (social, environmental, economic) and goal 2c (accessibility, health and safety). This indicator requirement was the most important as it defined the index and ensured that each of the indicators selected met the requirements of the index and the research behind it. For simplicity, six indicators were selected based on their individual characteristics and effectiveness, as a collection, to meet the CARTI goals. Each of these were subjected to a quality evaluation based on Table 5.8.

To do this, the longlist of grouped indicators was split into two separate lists based on the needs-based and capacity-based element requirements. A number of indicators were applicable to both indexes and were duplicated (see Appendix C).

Once split into lists, each indicator was assessed to see whether it met Index Goals 1 and 2a. Those that did not were removed. This generated two indicator shortlists for each CARTI element. These shortlisted indicators were then each given a score based on their relevance to each individual element of Goals 2b and 2c, with a score of 2 meaning major relevance, 1 meaning minor relevance and 0 meaning no significant relevance. From these tables, two Venn diagrams (Duignan, 2021) were produced to help visualise the results and the coverage of the indicators across the index goals. From these Venn diagrams, three indicators that met all the requirements of the selection process were selected. Further, these showed a good spread across index themes and strong potential for success.

Figure 5.1 shows the Venn diagram assessment for the needs-based shortlist of indicators. In the final shortlist there were ten indicators deemed suitable to represent the requirements of this element and these are shown in Figure 5.1. The three indicators highlighted in pink were carried forward to the evaluation stages, as they fulfilled the index goal requirements and were suitably spread across social, economic and environmental domains.

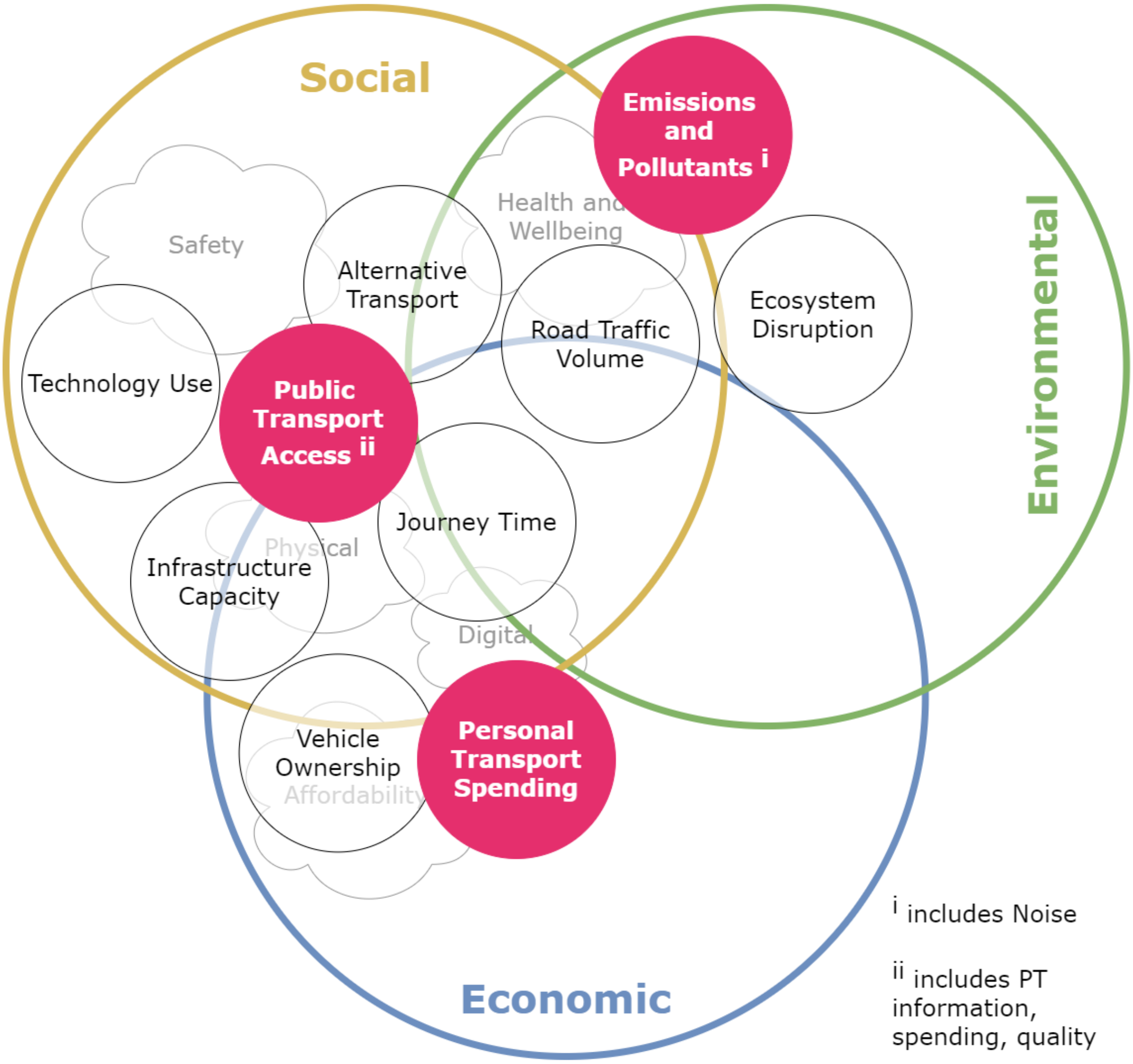


Figure 5.1 Needs-based indicator assessment

Emissions and Pollutants

This was the most common indicator used for transport and rural development indexes across the literature. It took many forms, ranging from simple CO_2 emission levels to including the full range of GHGs. In some cases, air quality was measured and compared to air quality standards or exceedance of historic levels (e.g., 1990), but these tended to feature in the older literature from the early 2000's. Despite its popularity, it does not cover a range of sustainability issues, being solely focused on the environment domain. However, there was a case to be made for the reduction of emissions improving the health and wellbeing of society. Also, indicators measuring social factors often directly relate to economic ones and vice versa, which can be a reason for environmental factors being perceived as less important. Therefore, a strong environment-focused indicator was required, and *Emissions and Pollutants* was the obvious choice. Further, this indicator covers many environmental factors and can be used as a partial measurement for other indicators, such as number of vehicles on the roads, a measure of alternative fuelled vehicles, road quality, ecological damage, and total green space.

Personal Transport Spending

This indicator was a popular economic indicator and variations of it were used across almost all the literatures considering the economics of transport development. Despite not being used in any rural development indexes, similar indicators such as *Household Income* can be associated with transport expenditure. Transport spending often consumes a large portion of household income in rural regions. Although a primarily economic indicator, this also records the important accessibility issue of economic accessibility; affordability. For rural dwellers, public transport systems need to not only exist and be available for use but must be affordable, as highlighted in the earlier chapters of this thesis and the elicitations conducted with transport planners.

If personal transport expenditure is high in comparison to total income, there is a need for more affordable transport systems. CAEV systems promise affordability, reducing the need for maintenance and human interaction, and offer a more convenient and reliable service. In this case, service quality and convenience could help justify costs, especially as they might be high in the initial implementation phases.

Public Transport Access

This indicator was amongst the most popular across both rural and urban scenarios. In each case *access* was measured differently but generally related to the proximity of public transport nodes with respect to population location. This indicator covers the social and accessibility domains primarily, but also economics related to public transport, in that public transport is intended to be cheaper than private personal transport. There are also environmental benefits to accessing public transportation over private vehicle ownership, especially as, at present, EVs are more expensive than more affordable, and environmentally destructive, second-hand internal combustion engine (ICE) vehicles.

Other indicators that were treated independently included *Active Transport Access* and *Alternative Transport Modes*. The former records the ability of populations to access safe and connected infrastructure, such as pedestrian footpaths and cycle lanes, the latter the availability of alternative transport, which differs depending on the scenario. As *Public Transport Access* refers to the proximity of road-based public transport (buses, taxies), alternative transport would therefore refer to trains, trams, and potentially active transport, thereby incorporating the *Active Transport Access* indicator. *Public Transport Access* also incorporates, to varying extents, other identified indicators, namely *Public Transport Quality*, *Information Availability* and *Concessionary Uptake*.

Figure 5.2 shows the Venn diagram assessment for the capacity-based shortlist of indicators. In the final shortlist there were nine indicators deemed suitable to represent the requirements of the capacity element. The three indicators highlighted in pink were carried forward to the next selection phases, as they fulfilled the index goal requirements and were suitably spread across social, economic and infrastructural domains.

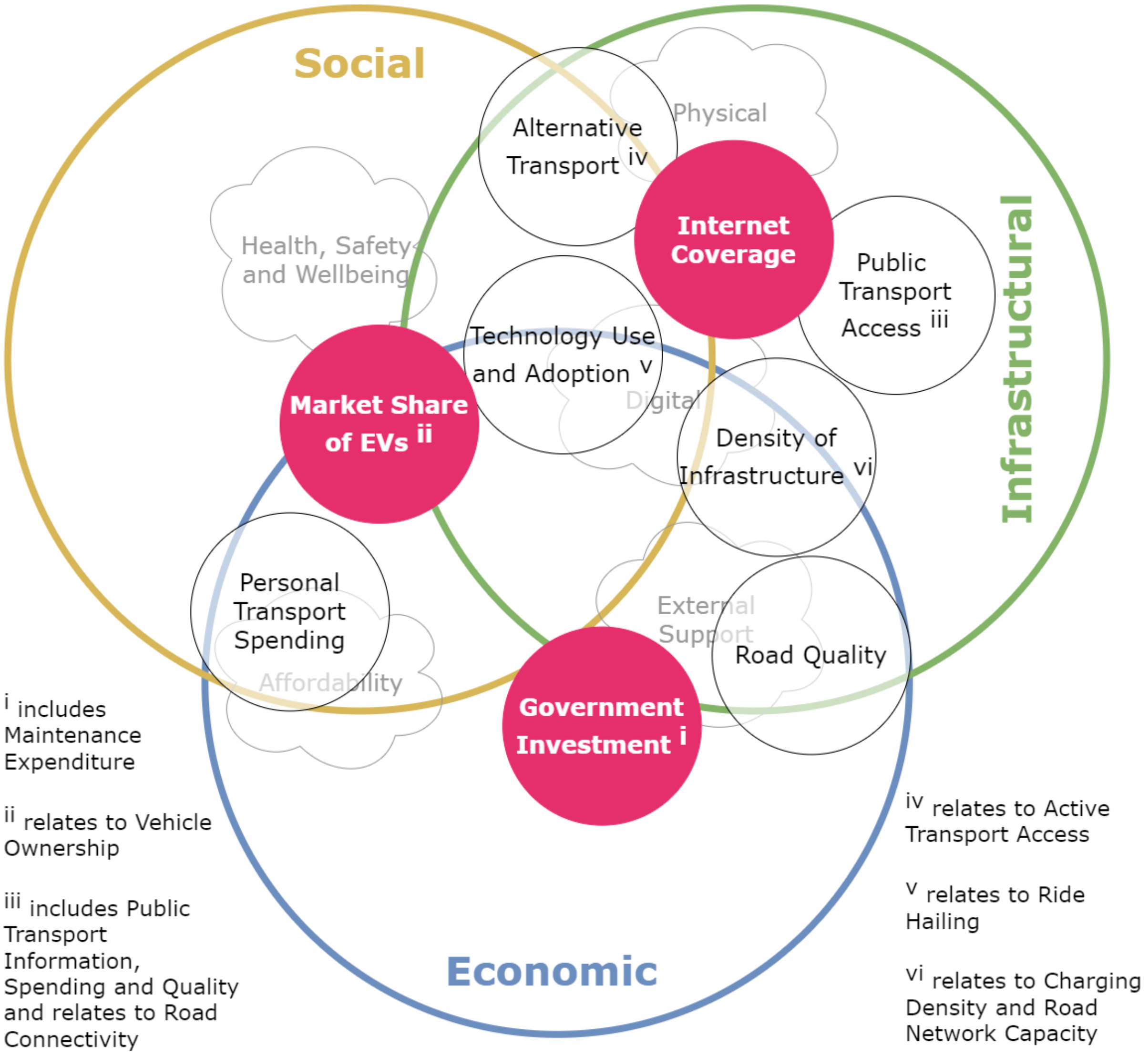


Figure 5.2 Capacity-based indicator assessment

Market Share of EVs

This indicator only appeared once during the indicator collection process, but it potentially describes a number of factors specifically related to CAEV technology adoption. Firstly, this is a direct indicator of EV uptake, which is a key prerequisite of CAEV technology implementation. It also implies the extent to which an area has appropriate EV charging infrastructure available. Secondly, as EVs are a relatively new emerging technology, many of these vehicles come with new CAV features including internet connectivity and driving assistance capabilities such as adaptive cruise control and lane assist. In the case of the popular Tesla models, there are also Level 3 automation features built in. Therefore, EV adoption can be linked to potential for, and various levels of, AV adoption. Finally, market share of EVs can highlight a social willingness and ability to adopt CAEV technologies, particularly with increasing smartphone-vehicle connectivity and the internet of things (IOT).

This indicator has a wide coverage across the identified domains, as it addresses digital and physical infrastructure requirements, societal acceptance and use of CAEV-related transport technologies and indicates the extent to which people are able to afford such technologies.

This indicator was taken from KPMG's AVRI report (KPMG, 2019). Therefore, the measurement of *Market Share of EVs* is originally at a national level. As such, a measurement method had to be identified to produce values at local rural levels as required by the index. Data including EV sales numbers was found to be useful.

Government Investment (in transport infrastructure)

This indicator was identified across seven different indexes during the collection process due to its wide influence on many factors relating to rural and transport development. In this case, *Government Investment* is related to transport infrastructure in general, rather than uniquely CAEV infrastructural and technological investment. It will be used to identify priority rural areas for investment, with the specifics of where the investment will be spent up to planners and decision makers. This indicator covers the important economic themes highlighted as well as representing a number of infrastructure-specific indicators relating to infrastructure quality and maintenance. This indicator therefore suggests a suitable physical infrastructure environment for CAEVs to operate in. In Chapter 4, planners and professionals identified the condition and quality of infrastructure to be a minimal barrier to CAEV adoption, disagreeing with the assumptions in Chapter 3. Therefore, the capacity element focuses on the potential investment in physical infrastructure to drive CAEV growth and use, rather than the actual quality of the infrastructure itself.

Internet Coverage

Chapter 3 and 4 highlighted the extent to which CAEVs will have to rely on digital infrastructure. Therefore, the internet coverage indicator has been selected to directly cover the digital infrastructure sub-theme. Internet coverage is generally poorer in rural areas than urban areas and this has been referenced repeatedly throughout this thesis. This makes this indicator a critical component of the capacity element of the CARTI, primarily due to CAEV reliance on internet connectivity, but also secondly to highlight the lack of rural capability. This then refers back to the needs-based index.

This indicator directly covers the digital infrastructure sub-theme and, with it accounts for societal use and acceptance of technologies that are reliant on use of the internet, in similar fashion to *Market Share of EVs*. There is also an economic element reflected in the distribution of internet provision, where external investment and support is required to provide internet access to rural areas.

5.6.5 Indicator Quality Evaluation (step vii)

In order to assess the quality of the selected indicators, a proposed measurement method for each of the indicators was needed. Based on these measurement methods, data type and data source, the five quality criteria could then be applied.

The measurement method of each indicator was determined based on existing literature and any available data. Each of the sources used to extract the original 202 indicators either explicitly defined the method of data collection themselves or stated the original source from which the indicator was taken. A combination of these existing methods and sources, consideration of the importance placed on this index being rural-centric and the need for a relatively small geographical scale in which to assess and apply the indicators, resulted in the measurement methods described in Table 5.9, which defines each of the relevant measurement methods used for each of the six initially selected indicators. Details of each measurement method and the application of those methods are described in detail in the following section of this chapter.

Table 5.9 Initial selected indicators and their proposed measurement methods

CARTI Element	Indicator	Units	Measurement Method
Needs-based	Emissions and Pollutants	Annual tonnes of CO2 per capita (tpppa)	Total annual road transport CO_2 emissions by local authority region derived from UK government data divided by the total population of the local authority region.
	Personal Transport Spending	Proportion of total weekly expenditure (%)	Mean average of personal transport spending by region and rurality divided by the total weekly expenditure by region and rurality as a percentage.
	Public Transport Access	Proportion of population within walking distance of public transit stops (%)	GTFS data derived from UK government data and GIS proximity methods using ESRI ArcGIS Pro determine the total population within BREEAM recommended maximum walking distance of a bus stop, divided by the total population as a percentage based on rurality.
Capacity-based	Market Share of EVs	Proportion of total cars licensed as EVs (%)	Total number of EVs licensed divided by the total number of cars registered as a percentage, derived from UK government data.
	Government Investment	Total investment per capita (£pp)	Total investment in transport and transport infrastructure divided by total population by local authority, derived from UK government data.
	Internet Coverage	Proportion of roads with 4G coverage (%)	Proportion of A and B roads within a local authority with no reliable 4G mobile internet, derived from raw UK government data.

An evaluation of each indicator, and their measurement methods, against the five quality criteria from Table 5.8 was conducted and the results are shown in Table 5.10. The extent to which each of the criteria is met is noted and any issues that might arise with meeting the criteria are highlighted.

Each of the selected indicators passed each of the quality criteria based on the measurement methods described. Some issues were noted but did not substantially impact the achievement of the quality criteria to an extent that warranted the selection of an alternative indicator.

Following the quality evaluation, this chapter has described the initial selection of three indicators for each CARTI element, totalling six CARTI indicators. Based on the application and analysis of this collective index, in addition to the CARTI's application and case studies described in Chapter 6, further iterations of any of these processes could be performed to further build the index to select alternatives or include more indicators.

Table 5.10 Indicator quality assessment with potential issues

Indicator	Availability	Measurability	Reliability	Understandability	Effectiveness
Emissions and Pollutants	Data easy and free to access	Data is measurable	From reliable government source	*Per capita output aids understanding but may require some user understanding of CO2 emissions*	Independent and contributes to project objectives
Personal Transport Spending	Data easy and free to access	*Requires some interpretation and interpolation*	From reliable government source	Percentage result easy to understand	Independent and contributes to project objectives
Public Transport Access	Data easy and free to access	*Requires major manipulation but applicable across study areas once method established*	*From reliable government source, however the manipulation method may be disputed*	Percentage result easy to understand once data is manipulated given that a reliable method is used	Independent and contributes to project objectives
Market Share of EVs	Data easy and free to access	Data is measurable	From reliable government source	Percentage result easy to understand	Independent and contributes to project objectives
Government Investment	Data easy and free to access	Data is measurable	From reliable government source	*Per capita output aids understanding but may require some user understanding of household expenditure*	Independent and contributes to project objectives
Internet Coverage	Data easy and free to access	*Measurable but at a larger geographic scale than the other indicators – impossible to distinguish between local authorities within the same county*	From reliable government source	Percentage result easy to understand	Independent and contributes to project objectives

5.6.6 Indicator Measurement Methods

Geographic Information Systems (GIS) are functionally powerful in processing and representing spatial features and their relationships. As the proposed indicators aim to represent a spatial problem, GIS is an appropriate tool to use to measure, apply and share the indicators and their collective index. Further, GIS is crucial for policy design and in aiding understanding and engaging practitioners (Cheng et al., 2007). GIS is a critical component of the final stages of this thesis, in which case studies are investigated and practitioners engaged to assess the validity and usefulness of the index.

Following the indicator selection and assessment process, Table 5.11 describes the measurement methods and sources used to define and calculate each of the six indicators. Once calculated, these indicators were applied to each local authority area in England.

In addition to Table 5.11, the following sub-sections detail the indicator measurement methods which involved more significant data manipulation and analysis. Data for the selected indicators was found at a range of geographical scales. However, for the greatest impact, the smallest possible geographic scale of data that could be used for each indicator data was selected. With the exception of *Personal Transport Spending*, the smallest geographical scale available across the indicators was found to be the local authority scale. To apply the data to each local authority, the boundaries which define Local Authority Districts 2020 (LAD20) were used (ONS, 2021c). This data was available in both spreadsheet and shapefile form for use with the GIS software ArcGIS Pro.

Table 5.11 Selected indicator measurement methods and data sources

Indicator	Unit and Measurement Method	Source	Geographical Scale
Emissions and Pollutants	Annual tonnes of CO2 per capita (tpppa). Total road transport CO_2 emissions divided by the total population.	UK local authority and regional carbon dioxide emissions national statistics: 2005 to 2019, 2005 to 2019 local authority carbon dioxide (CO2) emissions dataset (revised) (.csv format) (BEIS, 2021).	Local authority

Personal Transport Spending	Proportion of total weekly expenditure spent on transport (%). Mean average of personal transport spending by region and rurality divided by total weekly expenditure by region as a percentage. Further details on calculations can be found later in this section.	Family spending workbook 3: expenditure by region, FYE 2020 edition of this dataset (.xlsx format) (ONS, 2021b).	By region and whether classified urban or rural
Public Transport Access	Proportion of total population within walking distance of public transit stops (%). GTFS data and GIS proximity methods determine the total population within BREEAM maximum walking distance of a bus stop divided by the total population as a percentage. Further details on calculations and GIS methods can be found later in this section.	England bus open data (.gtfs format) (DfT, 2021a). Lower layer Super Output Area (LSOA) population estimates, Mid-2020: SAPE23DT2 edition (.xlsx format) (ONS, 2021a, ONS, 2021d). OS Open Roads (.shp format) (OS, 2021).	Local authority
Market Share of EVs	Proportion of total cars licensed as BEVs (%). Total number of BEVs licensed divided by the total number of cars registered as a percentage.	Licensed vehicle and ultra-low emissions vehicles (ULEVs) statistical data sets, VEH0105: Licensed vehicles by body type and local authority: United Kingdom (.ods format), VEH0132a Licensed ultra-low emission vehicles by local authority: United Kingdom (.ods format) (DfT, 2021b).	Local authority
Government Investment	GBP per capita spent on transport (£pp). Total investment in transport and transport infrastructure divided by total population.	Local authority revenue expenditure and financing England: 2019 to 2020 individual local authority data, Revenue outturn highways and transport services (RO2) 2019 to 2020 (.ods format) (MHCLG, 2021)*.	Local authority
Internet Coverage	Proportion of roads with reliable 4G coverage (%). Full coverage minus the raw data of the proportion of roads without reliable 4G coverage.	Ofcom Connected Nations (previously called Infrastructure Report) - UK internet speeds and coverage: broadband, Wi-Fi and mobile: Mobile local authority area by A and B road (.csv format) (Ofcom, 2018).	Local authority

*The Ministry of Housing, Communities & Local Government (MHCLG) is now called the Department for Levelling Up, Housing and Communities (DLUHC).

When using data at the local authority level the Rural Urban Local Authority Classification (RULAC) categorises districts and unitary authorities on a six point scale, based on the share of the resident population that resides in rural areas (Bibby and Brindley, 2017, DEFRA, 2016).

1. Mainly Rural (80% or more of the population resides in rural areas);

2. Largely Rural (Between 50% and 79% of the population resides in rural areas);

3. Urban with Significant Rural (Between 26% and 49% of the population resides in rural areas);

4. Urban City and Town;

5. Urban with Minor Conurbation;

6. Urban with Major Conurbation.

The specific RULACs for each local authority in England were found in the 2011 Rural Urban Classification lookup tables for all geographies under the LAD20 boundaries (DEFRA, 2021).

The indicators *Emissions and Pollutants*, *Public Transport Access*, and *Government Investment* each required the population statistics of a local authority to calculate. To calculate *Public Transport Access* (see following sub-section) population statistics for Lower layer Super Output Areas (LSOA) were used (ONS, 2021d). However, the total populations for local authorities were needed for all three of these indicators. Data for these total local authority populations were found from the Office for National Statistics (ONS, 2021a).

An analysis using ArcGIS Pro was performed to assess whether the two sets of population statistics were equivalent. The total local authority populations for each area were compared with the LSOA populations that were summed together within their respective local authority areas. In general, it was rural classified local authorities for which both set of data resulted in approximately the same total populations, with more urban local authority having larger discrepancies. For example, for Derbyshire Dales, a RULAC classification 1 area, the percentage difference between the local authority population estimates and the summed LSOA population estimates was 0.13%. For Nottingham, a RULAC classification 4 area, the difference was 23.43%. This was found to be due to 26 of the LSOA results containing "null" population data hence accounting for the large discrepancy. Due to potential "null" values across this data set, the total populations using local authority estimates were used to calculate each of the three indicators.

Measuring Personal Transport Spending

Data for *Personal Transport Spending* was only available at the regional scale. This was due to the method in which the survey was conducted, which was nationwide and completed voluntarily by households. There were not enough responses to be able to reasonably distinguish household spending at smaller geographical scales. Despite this, the data could be further refined using the differences in spending between urban and rural areas. Therefore, each region of England for which data is available for *Personal Transport Spending* was further split by rural and urban data distinctions. By averaging the results for each region with whether a local authority within that region is classified rural (1, 2, 3) or urban (4, 5, 6) a more focused *Personal Transport Spending* result was calculated, albeit not at the same level of accuracy as the other five indicators where data at the local authority level was available.

Measuring Public Transport Access

The definition of *Public Transport Access* used for the CARTI was the proportion of the population within reasonable walking distance of a public transit stop, in this case bus stops (BRE, 2017, Roberts et al., 2006, Sustainable Mobility for All, 2019). The definition for reasonable walking distance was taken from the BREEAM Communities Technical Manual, which states that the maximum walking distance to the nearest public bus stop is required to be 650 meters in urban cases and 1,300 meters in rural cases (BRE, 2017). Table 5.11 describes the use of General Transit Feed Specification (GTFS) data, which defines the locations of bus stops in

England, LSOA population estimates, for which centroids were generated based on the geographical boundaries of each LSOA, and the calculation of walking distances from these populations to their nearest bus stop, using the OS UK road network (OS, 2021).

This analysis was completed using ESRI ArcGIS Pro and its Network Analysis extension (ESRI, 2021a). ESRI ArcGIS is a subscription software paid for by the University of Nottingham and used by its students. To improve the accessibility of this index, ideally a free open-source GIS software such as QGIS would be used in future iterations of the method to calculate the *Public Transport Access* indicator. The steps taken to calculate the *Public Transport Access* indicator values were as follows:

1. Create a feature dataset within the project geodatabase (Create Feature Dataset tool);

2. Import GTFS, LSOA populations, LSOA boundaries, OS Open Roads and local authority boundaries data and convert to feature classes (Feature Class to Feature Class tool) with the same coordinate system (British National Grid);

3. Clip all features to within England local authorities (Clip tool);

4. Find the geographic centroids of each LSOA boundary (Mean Centre tool) and apply LSOA population data to these centroids;

5. Snap point locations (LSOA centroids and GTFS bus stops) to OS Open Roads network;

6. Join LSOA population centroid data to the local authority boundaries within which they are contained (Join tool) and export as a new feature class (Feature Class to Feature Class tool);

7. Create a network dataset (Create Network Dataset tool) within the feature dataset including the network features for analysis (OS Open Roads, GTFS bus stops, and LSOA population centroids);

8. Under the Network Dataset properties select the travel mode tab and set up the following settings:

    a. Type: Walking;

    b. Costs, Impedance: Length (meters);

    c. Restrictions: A Roads – Avoid, Motorways – Prohibited.

9. Use the Build Network tool and input the modified Network Dataset;

10. Use the Network Analyst extension to perform an Origin-Destination Matrix analysis;

    a. In this analysis, the Origin-Destination Matrix is programmed to find and measure paths less than 650 and 1,300 metres (BRE, 2017) along the network from a population centroid to the nearest GTFS bus stop. The Origin-Destination Matrix generates a straight line from a population centroid to its nearest bus stop within the limited distances defined. However, the value stored in the line attribute table reflects the network distance, not the straight-line distance visualised. This simplifies the visualisation and reduces computation time (ESRI, 2021b).

11. Based on the Origin-Destination Matrix results determine the total population (sum of population centroids) within each local authority boundary beyond reasonable walking distance to their nearest bus stop. This provides a value for the total population without reasonable access which can be transformed into a percentage based on the total population of that LA.

Due to errors and “null” values in both GTFS bus stop and LSOA population data a number of corrective measures were applied. Eight local authority regions record “null” populations in their LSOA data, so the average public transport access results for their respective rural classification were applied to each one. Further issues and associated mitigations are discussed later in this chapter.

5.6.7 Indicator Results and Performance

Based on the calculation methods described in Table 5.11 and the further details described in the previous section, values for each indicator were calculated for each of the local authorities in England inclusive of each RULAC from one to six. Each set of results were generated in either Microsoft Excel or ESRI ArcGIS Pro and imported into Microsoft Access to simplify organisation, support the assessment of the results and aid preparations for the formation of the collective index. The raw indicator results can be found in Appendix C.

To assess the results of the indicator calculations, statistical methods were applied to each set of results to determine any data outliers. Initially, boxplots were used to identify outliers (Dawson, 2011, Tukey, 1977). The most extreme, "far-out", outliers were identified as being those beyond three times the interquartile range (IQR) with less significant "outside" outliers identified as those within three times the IQR but beyond 1.5 times the IQR (Kaliyaperumal et al., 2015, Schwertman et al., 2004). Once identified, these outliers were reviewed in the context of the rest of the data. The outliers deemed to be unrealistic were replaced with the mean value dependent on the rural classification of the local authority where appropriate. Where the data was missing for an indicator, the mean average was also applied dependent on the rural classification, to maintain a full set of data across the indicators for each local authority area.

Emissions and Pollutant Results

For road-based CO2 emissions outside outliers were identified. A review of the data found these outliers to be reasonable. No far-out outliers were identified exceeding three times the IQR. No data was found to be missing.

Personal Transport Spending Results

For personal transport spending no outliers were identified. No data was found to be missing.

Public Transport Access Results

For the *Public Transport Access* there were 23 far-out outliers identified for mixed rural and urban classified local authorities. Whilst urban local authorities have a lower mean value for public transport access, which supports the assumption that urban environments have better access to public transport than rural environments, three of the four most extreme outliers were classified urban and were well beyond reasonable values for this indicator.

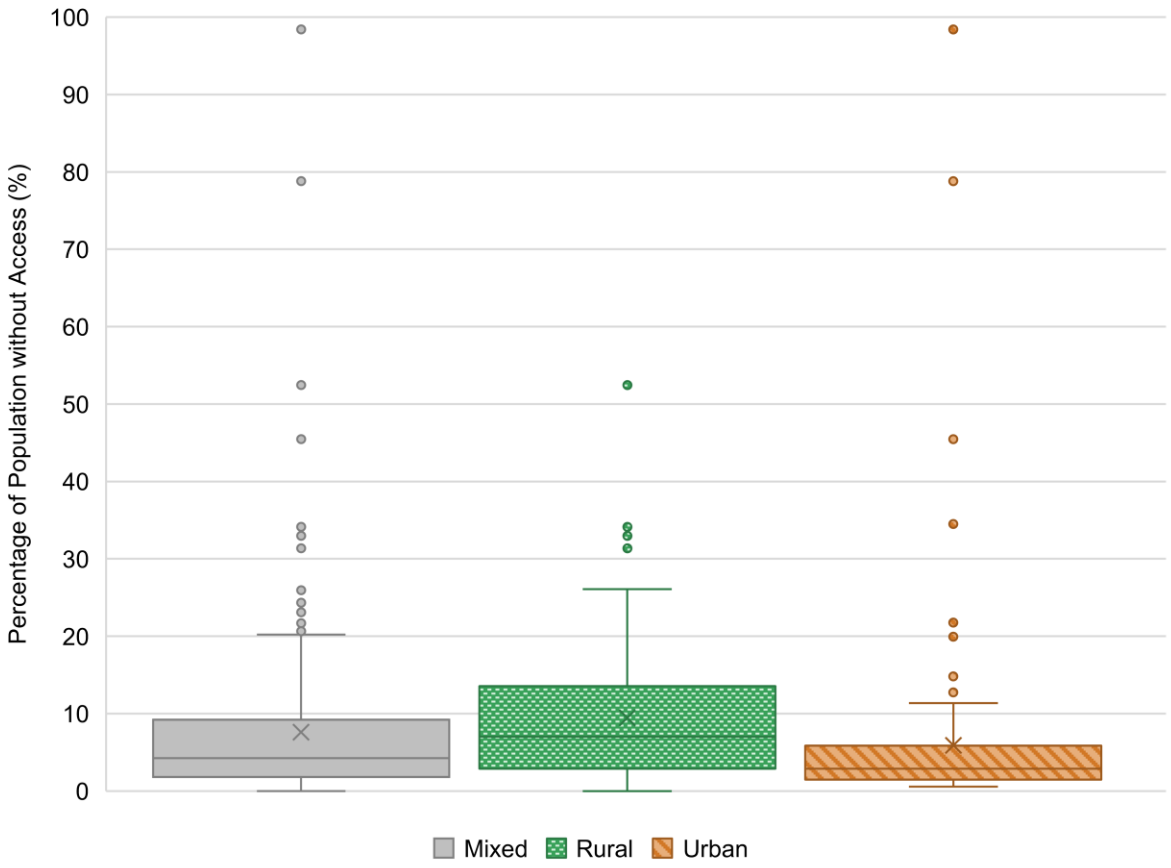


Figure 5.3 Data outliers for *Public Transport Access*

Figure 5.3 shows the *Rural Transport Access* results split into rural and urban classifications, with the mixed box and whisker diagram for comparison. With the urban values removed, the rural diagram has a greater range and captures many of the previously outlying rural values. Without the rural values, the urban diagram range becomes tighter and reveals more urban classified outliers. There is a dramatic range of values within the urban classification for the *Public Transport*

Access indicator with a mean of 5.889, median of 2.856, minimum value of 0.000 and maximum value of 98.422. These unreasonably extreme outliers were found to be due to errors in original GIS data used to generate these accessibility values.

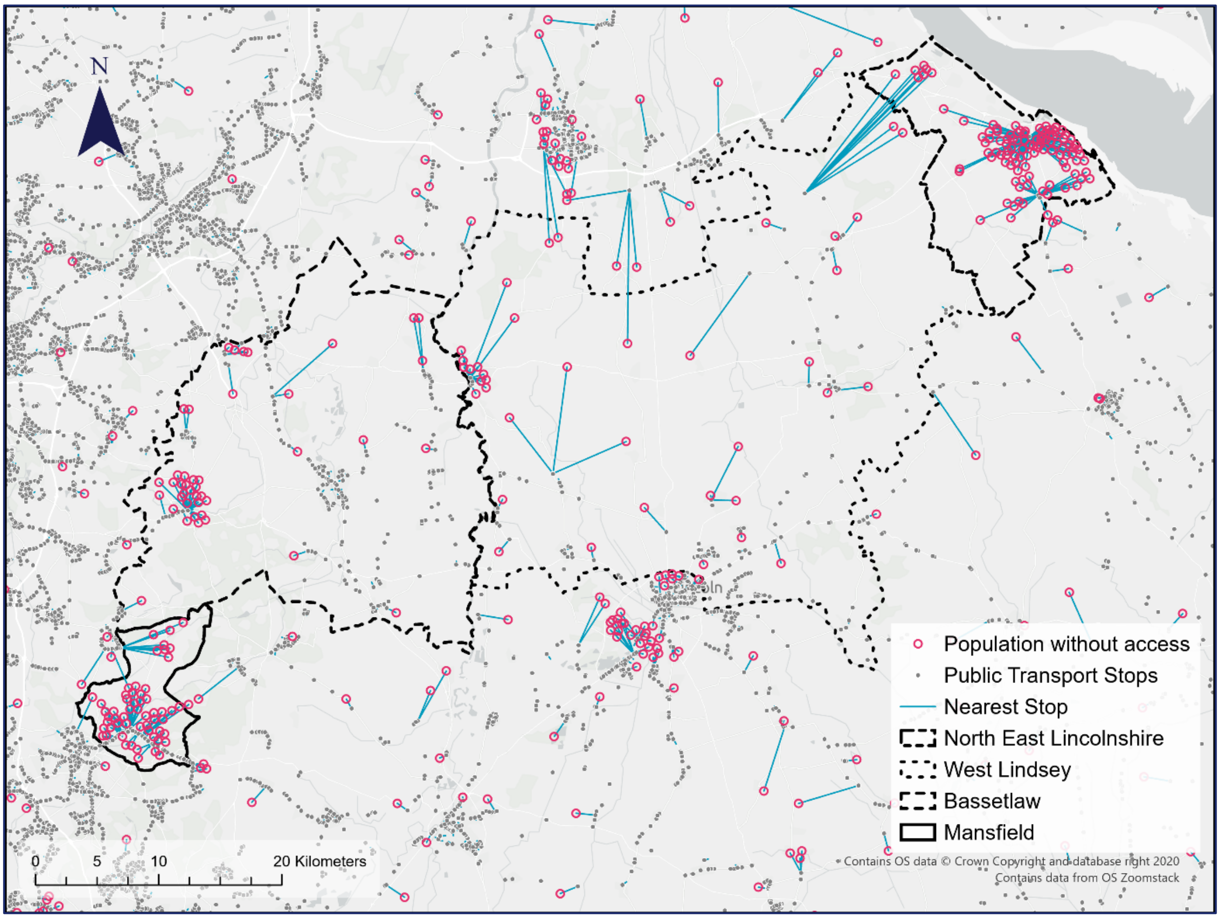


Figure 5.4 East Midlands *Rural Transport Access* GIS analysis

As examples the extreme urban outliers of North East Lincolnshire and Mansfield (Figure 5.4) highlight issues with GIS data quality and consistency. In both cases, there are significant numbers of public transport stops missing (vacant from the original GTFS data file), resulting in large walking distances from population centres to the 'nearest' public transport stop.

The rural box and whisker plot for *Public Transport Access* in Figure 5.3 has a more reasonable range of values with less dramatic outliers and a greater range. The mean is 9.438 and the median 7.019. However, whilst three of the outliers lie within the extreme outlier range of three times the IQR, one outlier with a value of 52.466 required further investigation.

The region south-west of North East Lincolnshire is West Lindsey (Figure 5.4), a rural classified local authority. As these are neighbouring, it is likely that West Lindsey also suffered from a lack of GTFS data. An additional factor that may have contributed to the high inaccessibility value is the distribution of population centres which have been snapped to their nearest road. In the case of West Lindsay (Figure 5.4), where populations are widely distributed, it is likely that the nearest roads to the defined population centres are non-major rural roads, where bus routes are less likely. The data for the other five indicators for West Lindsey are reasonable; therefore, rather than remove this region from the study entirely, the abnormal value for the *Public Transport Access* indicator was replaced with the average rural value of this indicator, for rural areas with the classification of 1.

Bassetlaw (Figure 5.4) is the most outlying of the group of three between the values of 30% and 40% for *Public Transport Access* (Figure 5.4). Further investigation found this region to border both West Lindsey in the east and Mansfield to the South West (Figure 5.4). Both these regions were found to lack GTFS data. Similarly, in Figure 5.4, Worksop in particular, an urban town in the west of the region, appeared to lack public transport stops, despite a quick search using Google Street View determining this not to be the case. This therefore skews the results of this region to be lacking *Public Transport Access* and the value for this indicator in this case was also averaged.

The next two outliers between 30% and 40% in Figure 5.3 were the local authorities of Copeland and Eden, both regions in the North West of England, significant portions of which lie within the Peak District National Park (PDNP). Despite similar *Public Transport Access* scores to Bassetlaw in the East Midlands (Figure 5.4), these regions are in a different part of the country and do not share the same characteristics with the towns within the local authority which feature realistic numbers and distribution of public transport stops (see Whitehaven, north-west, Figure 5.5).

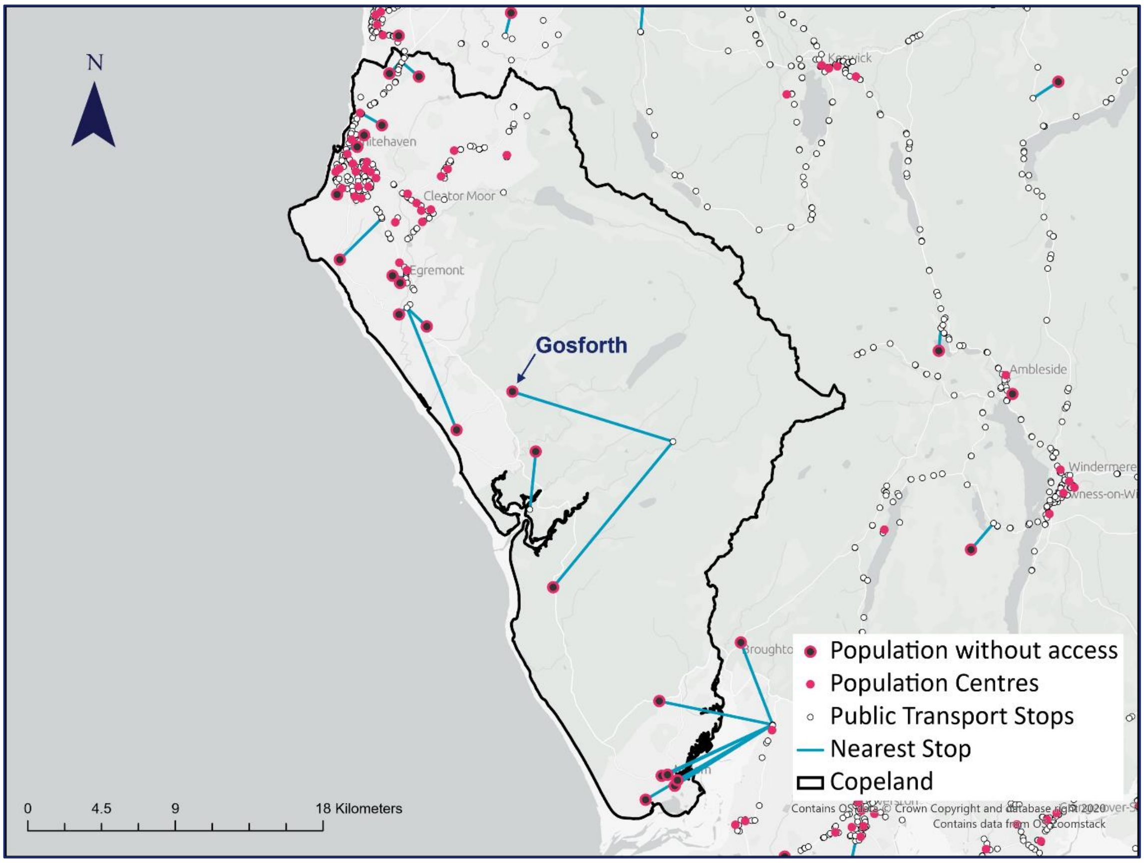


Figure 5.5 Gosforth, Copeland *Rural Transport Access* GIS analysis

An investigation into Gosforth, a small village in the centre of Copeland (Figure 5.5) revealed that the large distance identified to the nearest public transport stop may not be an exaggeration. Using the Google Maps directions service, no public transit directions could be found from Gosforth to any of the larger built-up areas in the Copeland region. Further, a search of the area using Google Street View found a disused bus stop bay on the A595 road northwest of Gosforth (Figure 5.6). This continues to highlight the underserved nature of rural areas regarding public transport services, and in this case the loss of such services that were previously available.

Figure 5.6 A disused bus stop bay on the A595, Copeland (Google Street View)

Eden demonstrated similar characteristics to Copeland and therefore both outlying values were assumed to be reasonable estimates of public transport access in both these rurally classified local authorities.

The remaining values of rural access for each remaining rural local authority were found to be within 1.5 times the IQR and therefore assumed reasonable estimates of public transport access.

The mean averages calculated to replace the outliers were based on the rural classification of each local authority, as there were correlations between the results and their respective local authority's rural classification. These distinct averages are clearly identifiable and shown in Table 5.12. These averages were also applied to the seven local authorities that had a null score due to data errors in their LSOA population centroids.

Table 5.12 Mean rural transport access results for each rural classification and modified local authorities

Rural Classification	Mean (without outliers)	Rural local authorities to which means were applied
1	14.943	West Lindsey (E07000142) Cornwall (E06000052) Isles of Scilly (E06000053)
2	7.542	Bassetlaw (E07000171) Wiltshire (E06000054) Northumberland (E06000057) County Durham (E06000047) Central Bedfordshire (E06000056) Shropshire (E06000051)
3	4.185	Cheshire West and Chester (E06000050) Cheshire East (E06000049)

Figure 5.3 shows that in the case of the *Public Transport Access* indicator, even with the extreme errors removed, the urban results skewed the rural results resulting in a narrower IQR allowing urban bias to creep in. This contributes to the argument to remove the urban results entirely from the CARTI as suggested by the earlier literature review. Therefore, the urban results are removed to create a rurally biased tool to counter existing urban bias.

Market Share of EVs

Results for the number of registered EVs had a large and well distributed range, particularly in urban classified areas. As such, only one outlier could be easily identified. This most extreme value is for the Isles of Scilly, rural classification 1, which has the highest proportion of licensed EVs with a value of 7.970%. For comparison, the average across all English local authorities was 0.587% and the average of rural classification 6 local authorities being 0.713%. No data was found to be missing for this indicator.

Government Investment

There were two extreme outliers identified for *Government Investment*. One was the City of London with a value of £2,658.07 per capita (over 41 times the IQR), and the other was the Isles of Scilly, a classification 1 rural area over three times the transport investment of the urban local authority of Nottingham at £848.16 per capita. The average rural investment was £28.30 per capita. Due to the bias skew of the urban *Government Investment* values the removal of urban local authorities from this index was further supported. In terms of the high investment value for the Isles of Scilly this was not averaged due to the reliability of the data source. No data was found to be missing for this indicator.

Due to The Isles of Scilly ranking highest for both *Market Share of EVs* and *Government Investment*, this local authority was identified as a good case study to assess the validity and usefulness of this index, particularly as its internet coverage score is relatively poor. This case study can be found in Chapter 6.

Internet Coverage

Figure 5.7 shows the large variation between 4G road coverage between rural and urban classified areas. The rural box plot has a large number of outliers and greater range of values with an average coverage of 95.898%.

Investigation into the original raw government data of two most extreme outliers suggested that they may be reasonable estimates for their respective local authority's road-based 4G coverage. For example, Mid Suffolk scores poorly in terms of 4G signal in and outside of premises and geographically, scoring over three times the IQR in all cases compared to the average in rural areas. This consistency suggested the outliers were realistic and therefore they were not altered. No data was found to be missing for this indicator.

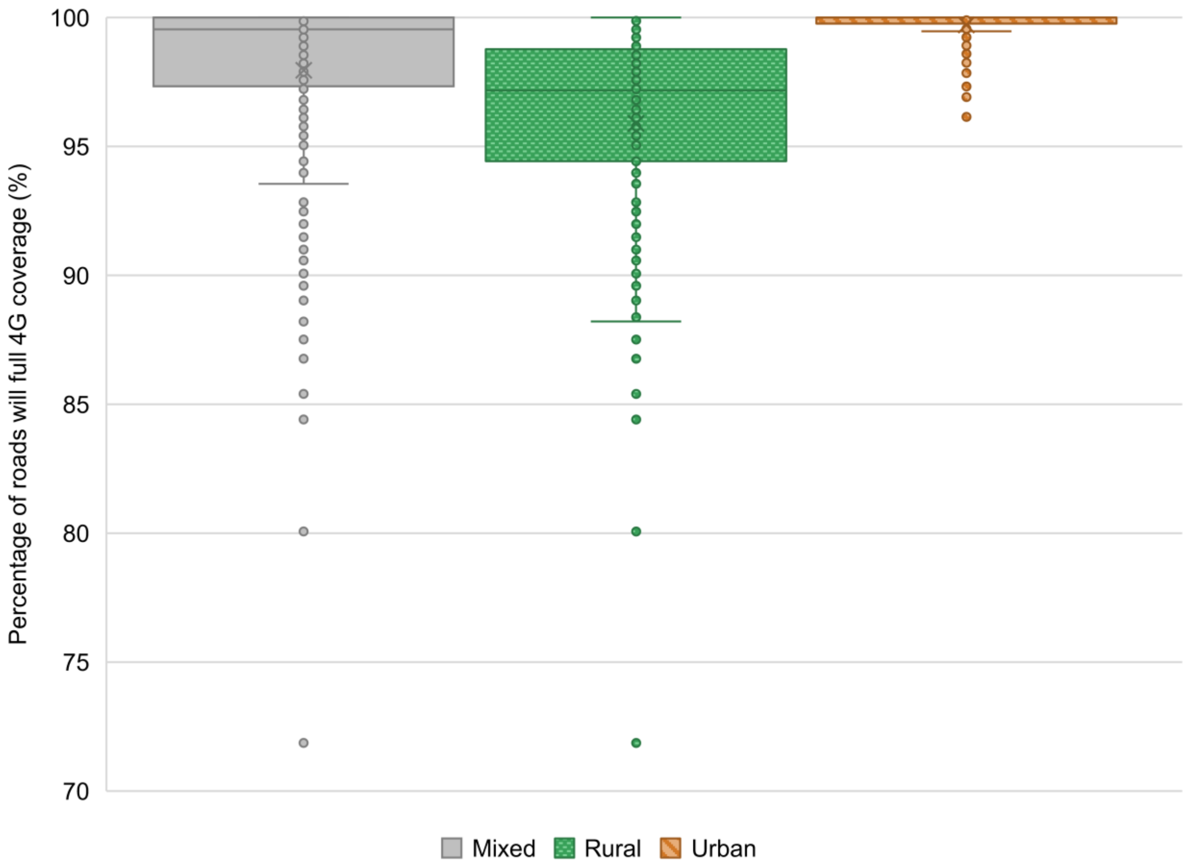


Figure 5.7 Data outliers for *Internet Coverage*

5.7 Index Construction (stage 3)

Six indicators were selected, measured for each rural English local authority, and the results were assessed to check their initial validity for use in the CARTI. For their collective use, they were scored and grouped to generate a useful and comparative index which assessed both a rural area's need for CAEV technology and its capacity to support CAEV implementation. Further, an overall CAEV potential score was calculated for each local authority to aid transport planner decision-making.

The CARTI scores produce values within bounds ($0 \leq \text{Index} \leq 100$) for effective analysis and comparison, and the calculation processes used to construct the index was designed to be clear to ensure that it's repeatability and useability by others

(Kim and Yang, 2016). For complete clarity, the CARTI was designed around a "one equation" index model (Kaufmann et al., 2007). Keeping the index calculation process simple, makes it easier for policy makers and the public to understand the CARTI, which was a key requirement of this index.

5.7.1 Scoring Methodology (step viii)

Scoring involved converting each of the indicator's alternatives (the varying values scored by each local authority) into a numerical score, normalised to be within the range of 0 to 100. In the case of the four indicators measured as a percentage (Table 5.11) the initial scoring was simple. For the remaining two indicators that outputted absolute alternatives (*Emissions and Pollutants* and *Government Investment*) a scoring method was applied. Scoring methods can be direct or indirect, with indirect methods often more valid and reliable. These indirect methods involved ranking preferred alternatives. In this case, the indirect Bisection Method (Von Winterfeldt and Edwards, 1986) was used. This method bases its scoring on the use of maximum and minimum alternatives. To apply this method, data for each rural English local authority was analysed and the maximum and minimum values applied. This provided the boundaries between which each rural English local authority was scored between 0 and 100. For consistency, the percentage values measuring the remaining four indicators were also scored between the highest and lowest percentage values.

Table 5.13 highlights these values for each of the six indicators. The indicator score, Y, for each indicator was calculated by finding the percentage value of each local authority indicator value, X, between the determined maximum, X_{max}, and minimum, X_{min}, values as shown in Equation 1.

$$Y = \frac{X - X_{min}}{X_{max} - X_{min}} * 100$$

Equation 1

Table 5.13 Indicator maximum and minimum values for scoring

CARTI Element	Indicator (units)	X_{max}, Maximum Value (Local Authority Name, Code)	X_{min}, Minimum Value (Local Authority Name, Code)
Needs-based These indicators are scored where a high score represents a greater need.	*Emissions and Pollutants* (annual tonne CO2 per capita)	3.874 (Rutland, E06000017)	0.196 (Isles of Scilly, E06000053)
	Personal Transport Spending (% of total expenditure in £ per week)	15.819 (Multiple)	15.016 (Multiple)
	Public Transport Access (% of total population outside of maximum acceptable walking distance of public transit)	32.964 (Copeland, E07000029)	0.000 (Multiple)
Capacity-based These indicators are scored where a high score represents a greater capacity.	*Market Share of EVs* (% of total cars licenced as BEVs)	7.970 (Isles of Scilly, E06000053)	0.180 (Redcar and Cleveland, E06000003)
	Government Investment (£ per capita)	848.158 (Isles of Scilly, E06000053)	0.644 (Broadland, E07000144)
	Internet Coverage (% of roads with reliable 4G coverage)	100.000 (Multiple)	71.830 (Mid Suffolk, E07000203)

5.7.2 Weighting the Indicators (step ix)

Following scoring, the need to apply weights to the indicators was considered.

Weighting involves determining the relative weights of each indicator normalised to unity to reflect each indicator's relative importance (Kaufmann et al., 2007). However, there is debate in the literature around the appropriateness of weighting, particularly for sustainability-based indexes such as the CARTI. Whilst, in some cases, weightings were based on relative importance, either judged by experts or the researchers' own subjectivity (De Toro et al., 2004, Hansen and Devlin, 2019), in others, weights were applied based on the recurring popularity of an indicator in past literature (Perujo et al., 2009, Pregl et al., 2008). In the case of the CARTI, which attempts to break away from the traditional transport development indicators, this latter weighting method would have been inappropriate. Weighting can also often leave indicators underrepresented, with expert weighting described as "subjective" and not transferrable across regions (Michalek and Zarnekow, 2012b). Further, sustainable solutions should aim to balance their impacts across social, economic and environmental domains, as was a goal of the CARTI, described in Table 2. This suggests that weighting is inappropriate as it can distort the careful balance of sustainability as judged by the indicator selection process. Other studies have come to similar conclusions, where indicators were themselves specifically selected to represent a balance of development aspects (Abreu et al., 2019, Kim and Yang, 2016). Therefore, each CARTI indicator was weighted equally. Further, the bisection method used to score the indicators is ineffective when weighting criteria (Hansen and Devlin, 2019).

5.7.3 Ranking Indicators with Scores and Weights (step x)

Given the maximum and minimum values for each indicator and Equation 1, each of the indicator values were converted into indicator scores between 0 and 100. Given that weights were not applied, each score had the same value across indicators and local authorities.

A number of studies in the literature suggested using the geometric mean. This is because the additive nature of the arithmetic mean leads to attempts to solve unbalanced problems with a balanced solution, sometimes resulting in extreme values that bias the result of the index (Abreu et al., 2019, Kageyama, 2008). However, the Bisection Method used to score the indicators meant that the poorest performing local authorities receive a score of zero. Zero scores are incompatible with the method required to calculate the geometric mean, as values must be greater than zero for this to be performed. Therefore, the arithmetic mean was used to generate need, capacity, and potential index scores. This was a suitable method given that no weights are applied.

Using the arithmetic mean, an element score for both CAEV need and capacity was generated, as well as a single total overall potential CAEV score, each between 0 and 100. Tables containing the raw indicator values, indicator scores, CARTI element scores and total index score can be found in Appendix C.

5.7.4 Supporting Decision-Making (step xi)

Figure 5.8 shows the three scoring stages and the relationships between indicators, elements and the whole index. Each stage was designed to be used to contribute to different levels of decision-making. For example, the overall CAEV Potential index score highlights target areas for further investigation into CAEV implementation; the element scores define to what extent a target rural area has the need for, or current capacity to support CAEV implementation; and the indicator scores highlight the specific issues relating to need or capacity to address in relation to CAEV implementation.

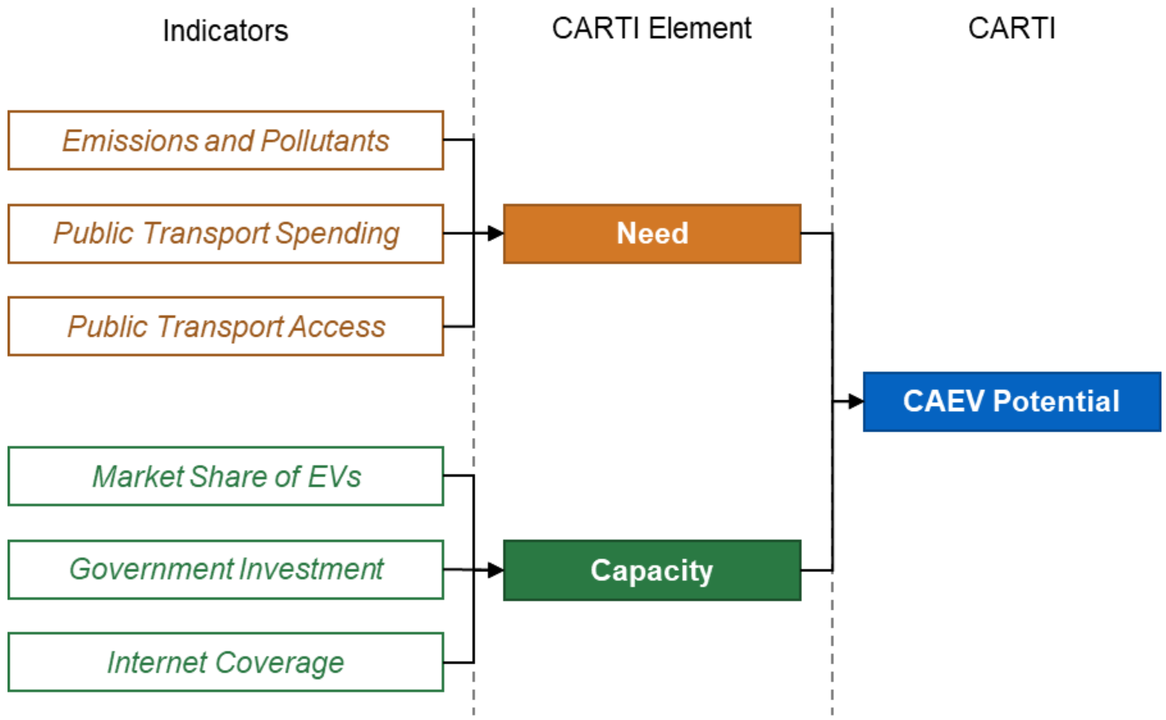


Figure 5.8 CARTI score levels

This chapter has provided a detailed account of the reasoning, theory and methodological development behind the CARTI. In conclusion, a three-stage dual-approach index was developed, designed to meet goals that were driven by the research aim and objectives of this thesis. The result is a simple but relevant index model for use by transport planning professionals to promote the implementation of CAEVs in rural areas. The CARTI is the proposed solution to the problems identified in the conclusions of Chapter 3 and Chapter 4, as it highlights the infrastructure requirements of CAEVs as well as providing a platform from which transport planners can understand rural transport challenges and develop specifically CAEV-based solutions. An assessment as to the validity and usefulness of the CARTI for CAEV implementation decision-making was conducted and is described in the following chapter, which also describes an evaluation into the CARTI's effectiveness at local authority and national levels.

6 CARTI APPLICATION AND EVALUATION

This chapter describes the application of the CARTI. To do this, three case studies were identified. Through the investigation of the case study areas and engagement with local professionals, who themselves had professional links to local transport ecosystems, the validity and usefulness of the CARTI and its indicators were assessed, as well as the potential for the CARTI to support transport planning decision-making. Chapter 6 concludes with a summary of the case study findings and a critical reflection from the DfT's Chief Scientific Advisor on the CARTI's potential from a national transport planning perspective.

Based on the methodological steps described in Chapter 5, for each predominantly rural local authority region in England a score was given for each of the nine elements shown in Figure 5.8. These scores were based on each individual local authority's unique social, economic or environmental statistical characteristics. The list of local authorities and their associated scores can be found in Appendix C. As the results were based on geographical regions, the scores were imported into ArcGIS Pro for visualisation and spatial data exploration purposes.

Figure 6.1 shows the CARTI results from the needs (Need Element Score) based and capacity (Capacity Element Score) based CARTI elements and the combined CARTI (CAEV Potential) Score, which highlights a local authority's potential to implement CAEVs based on its established need and capacity. The contrasting shades in the Need Element Score and CARTI (CAEV Potential) Score maps show a greater range of scores across the local authorities compared with the Capacity Element Score map, for which there is less contrast. This highlights the similarities across this CARTI element. This visualisation highlights a greater range of disparity across rural need for CAEVs, against a more universally consistent capacity to support CAEV implementation across the UK. Therefore, the total CAEV potential is more influenced by the differences in the needs-based element and its related indicator scores. This suggests that measuring need is more important than capacity and that any potential future rural CAEV implementation across the UK should consider the need of rural communities over their current infrastructural or economic capacity to support such implementation.

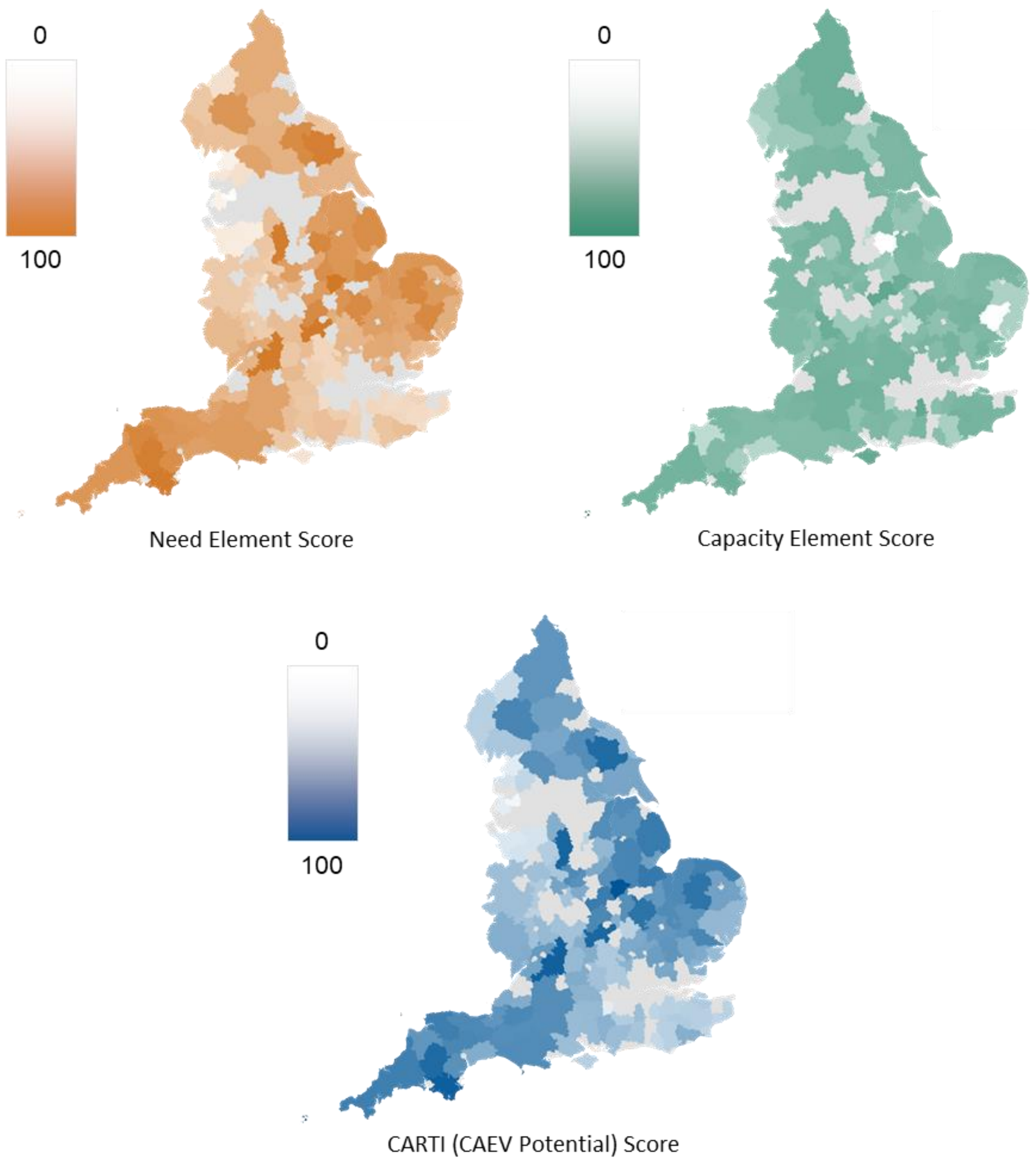


Figure 6.1 CARTI GIS results

6.1 Case Study Identification

Based on the CARTI GIS results in Figure 6.1, three local authorities were selected as case studies with which the validity and usefulness of the CARTI could be explored at the local authority level. The cases studies were selected based on their contrasting CARTI scores, geographical distribution, and due to transport and CAEV-related projects and trials occurring in those local authorities at the time. Figure 6.2 highlights the three selected case studies and their locations in England.

Figure 6.2 Identified case study areas

Table 6.1 describes further details of the case studies and the main reasons behind their selection.

Table 6.1 Reasons behind case study selection

Case Study Local Authority	Region	Reasons for selection
Derbyshire Dales	East Midlands	• Low *capacity* score; • High *need* score; • Average overall *CAEV potential* score; • Ongoing campaign for the reinstatement of the rurally significant Peaks and Dales railway line with potential to act as an infrastructural spine to support rural transport hubs and rural CAEV implementation.
South Lakeland	North West	• Low *capacity* score; • Low *need* score; • Low overall *CAEV potential* score; • Recently completed CAEV trials exploring public perceptions and implementation potential to serve communities and visitors at lake Windermere and other tourist hotspots.
Isles of Scilly	South West	• Average *need* score; • Very high *capacity* score (despite relatively low internet coverage); • High overall *CAEV potential* score; • Recently conducted autonomous drone trails for mail deliveries from mainland England to the Isles or Scilly and inter-island deliveries.

Table 6.2 compares the CARTI scores received by each of the selected local authority case studies based on the scoring methodology described in Chapter 5.

Table 6.2 Case study CARTI scores

Index / Indicator	Score (0 - 100)		
	Derbyshire Dales	South Lakeland	Isles of Scilly
CARTI	**55.9**	**32.5**	**70.0**
Need	**76.8**	**39.7**	**48.4**
Emissions and Pollutants	79.0	55.0	0.0
Personal Transport Spending	87.1	0.0	100.0
Public Transport Access	64.3	64.2	45.3
Capacity	**35.1**	**25.2**	**91.5**
Market Share of EVs	4.8	4.2	100.0
Government Investment	1.9	3.4	100.0
Internet Coverage	98.4	68.1	74.5

6.2 Case Study Methodology

Given the methodological extent of indicator selection and index development in Chapter 5, the review of these case studies addressed whether the CARTI was a realistic and applicable planning tool for use in real-world transport planning and decision-making scenarios. As such, this chapter describes an assessment of the practical extent of the CARTI's application, more so than an assessment of the CARTI methodology. However, some methodological improvements are discussed.

To conduct this investigation a second series of elicitations, as an extension to those described in Chapter 4, took place. These elicitations identified local professionals within transport-related disciplines within each of the three selected local authorities. These professionals partook in a workshop-style discussion with the researcher where they were asked for their critical perspectives on the CARTI, its validity, usefulness, and application potential within their region. Again, through purposive sampling, these professionals were either known to the researcher or were identified and contacted through the researcher's known networks. Whilst based on a workshop format, which enabled the researcher and participants to determine their own direction of discussion based on areas of interest and expertise identified in relation to the CARTI and its application, Appendix D details questions drafted by the researcher prior to the elicitations to help guide the discussions. Not all of the questions listed were explicitly asked in each elicitation. Appendix D also shows the rest of the case study workshop literature provided to participants, consisting of a simplified summary of the CARTI process and results.

The workshop sessions were conducted using Microsoft Teams and each session was recorded with the permission of the participant(s). These recordings were then transcribed and reviewed before being written up in the following case study analyses. Whilst live workshop sessions were conducted where possible, some participants were unavailable for these sessions and, as an alternative, submitted written responses to the workshop questions. The participant(s), or in the case of group responses the senior participant(s), for each case study were asked to give permission for the researcher to record their job title and employer information. Where permission was granted, these were used in the following case studies to support the reliability of the responses provided. None of the respondents are directly identified by name. Despite this, each participant was made aware that it may be possible for a reader to identify each participant based on this employment information and the time at which this thesis and its content was published. As for the ethical consideration described in detail in Chapter 4, this series of elicitations was approved by the University of Nottingham Faculty of Engineering Ethics Committee following an ethics application by the researcher. The ethics application and approval can be found in Appendix D.

The following chapter sections detail the analysis of these case study elicitations and discuss the potential impact of the CARTI on transport planning and decision-making for rural-based CAEV implementation. Included and discussed in each case study is an exploration of a local transport project recently or presently being conducted within the case study regions themselves. This chapter looks at the potential relationships between the CARTI and its results for potential CAEV implementation, alongside the characteristics of the transport projects and the potential for modal integration.

6.3 Derbyshire Dales

Derbyshire Dales is a local authority district in west Derbyshire in the East Midlands, England. Figure 6.3 shows Derbyshire Dales' position in the UK and highlights its major geographic overlaps with the geographic region of the Peak District National Park (PDNP). Figure 6.3 also shows the proposed alignment for the reinstatement of the Peaks and Dales Line (P&DL) and the line's proposed railway stations.

This case study explored the CARTI results for Derbyshire Dales in the context of its location and rural characteristics, as well as the potential modal integration of transport modes within Derbyshire Dales and the PDNP. Specific reference has been made to rail and the opportunities rail projects such as the P&DL reinstatement and other DfT Restore Your Railways (RYR) (DfT, 2021f) and Integrated Rail Plan (IRP) (DfT, 2021d) projects around the UK could provide for CAEV implementation.

To contribute to this case study, the researcher also reflected on a placement project in which the potential modal shift and associated carbon emission reduction due to the proposed P&DL reinstatement were investigated.

The Peaks and Dales Line (P&DL) once linked the county of Derbyshire from north to south, and the East Midlands region with Manchester and the North West of England. In 1968, the P&DL was closed following the publication of the Beeching Report in 1963, which ultimately saw thousands of miles of British railways closed (Beeching, 1963, DfT, 2021f). However, an ongoing campaign seeks to reinstate the P&DL (Figure 6.3) using the original track bed which has been preserved.

Portions of this track bed currently serve heritage rail services and make up the popular Monsal trail walking and cycling route in the PDNP.

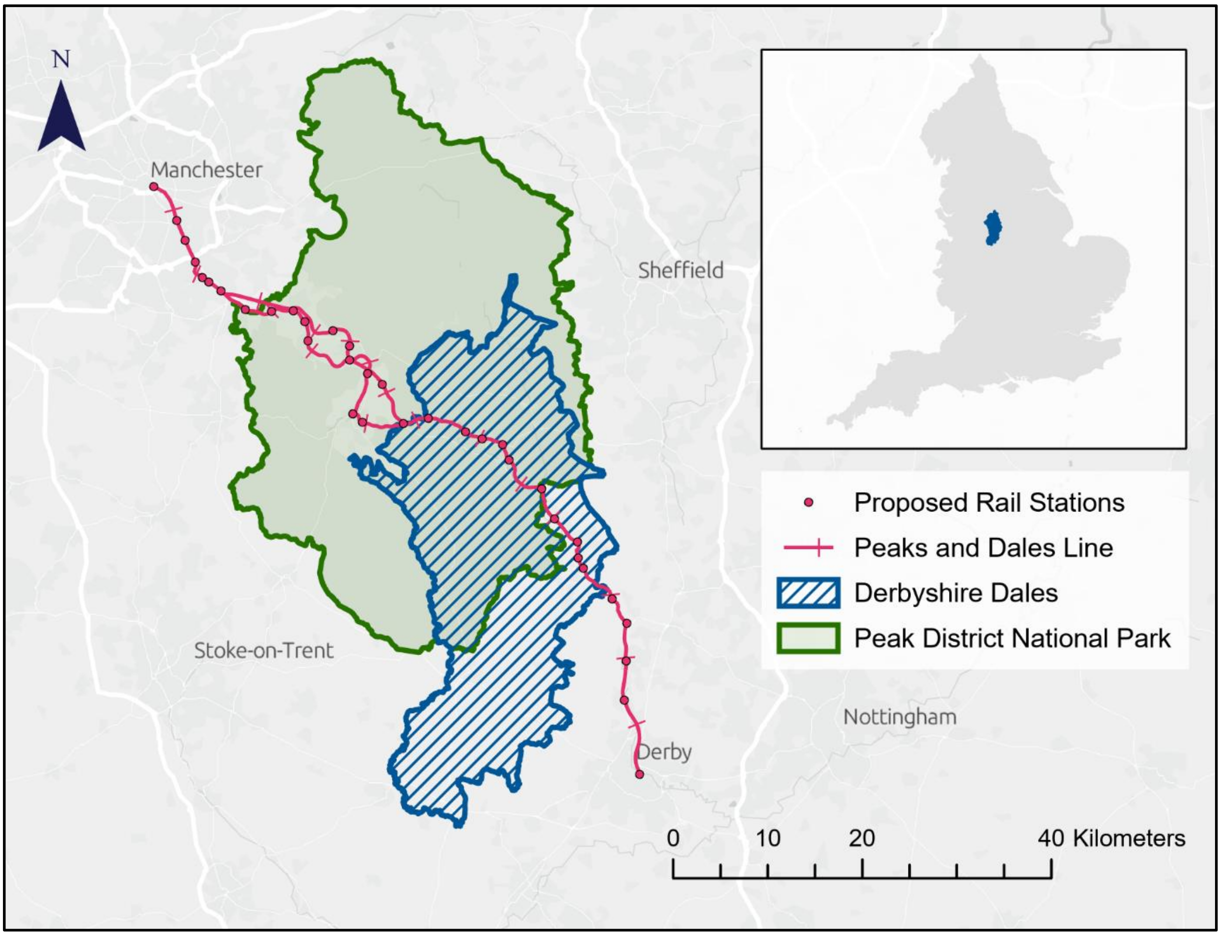


Figure 6.3 Derbyshire Dales and Peaks and Dales Line proposal

Campaigners for the reinstatement of the P&DL believe such a project would contribute to reducing Derbyshire's high surface transport carbon footprint, solve issues relating to limited public transport infrastructure in the region, and promote substantial modal shift (and behavioural change) away from private car use to reduce congestion in the region (Chaytow and Walters, 2021). Campaigners are also interested in promoting an integrated rail solution combined with active, shared and public transport last-mile solutions, using the proposed P&DL stations as transport hubs to serve the Derbyshire and Peak District regions.

Referencing the P&DL campaign, this case study has explored the potential for rural CAEV integration with the proposed P&DL rail reinstatement project and the opportunities and challenges that such integration may provide. The CARTI results

(Table 6.2) indicate that with increased investment and wider deployment of EVs, perhaps through EV charging infrastructure provision, Derbyshire Dales has the needs-based drivers for the successful uptake of CAEV-based transport solutions to support the proposed improvements to public rail in the region.

The following elicitation results describe the responses from rail transport professionals regarding the potential of the CARTI and its use in integrating rural CAEV solutions with those of rail. The participants in this study were all familiar with, and in some cases directly linked to, the campaign for the reinstatement of the P&DL.

6.3.1 Elicitation Results and Discussion

The validity, usefulness and application of the CARTI, the potential contributions the CARTI could offer the rail industry, as well as the extent of CAEV integration potential with the proposed P&DL were all discussed with rail professionals in and around the Derbyshire region who requested not to be specifically identified.

The following section highlights evaluative elements of the discussions regarding the CARTI, potential relationships and links between the CARTI, rail infrastructure and services, and the proposed P&DL. The perspectives provided by the participants were based on their personal experience working in a rail transport environment with rural connections.

Perspectives on Selected Indicators

One participant was unfamiliar with the indicators and their scoring methods and was reluctant to comment on their relevance or accuracy. This may have been due to their lack of experience in the road-based transport sector. Few of the indicators were relevant to rail and were specifically selected to assess road-based transport. However, given the participant's experience in the transport sector their unfamiliarity could indicate that the selected indicators were difficult to understand or apply to real-world transport decision-making scenarios.

> *"These are not data types I have ready and regular access to and so I cannot estimate the relevance."*

The CARTI was developed with a minimal number of indicators in an attempt to simplify the problem of rural CAEV implementation. As such, discussion moved to the extent to which the selected six indicators covered the problem of CAEV implementation and whether any of the indicators were irrelevant. Discussion took place around the potential to replace the existing indicators with more relevant indicators or whether additional indicators were required. Referring to electric charging infrastructure, the extent of which is inferred by the *Market Share of EVs* indicator, one participant suggested that *Electric Capacity* would be a useful indicator to show the reliability of the electric power network in the region. Whilst the electrification of rail was once distinct from ICE road transport, the emergence and rapid adoption of EVs has resulted in the need for the National Grid to share electricity between transport modes. Further, with concerns about fluctuating renewable energy methods and national electricity consumption continuing to rise, capacity and the reliability of supply was a concern.

> *"Electric Capacity available in the area would be crucial [as the] network can be limited and fragile."*

Electric Capacity is an interesting indicator to consider, although it would most likely be an addition to the existing indicators. Alternatively, it could replace *Market Share of EVs* to encompass broader infrastructural challenges and capacity issues. However, *Market Share of EVs* contains an important social capacity element regarding the social acceptance of EVs, which would be lost if this indicator were replaced.

Public Transport Access, the most data intensive and methodologically involved indicator, was criticised for not exploring accessibility far enough. One participant noted that, whilst it was a useful indicator highlighting the extent of public transport infrastructure, there was no element that described "what [the public] were accessing and with what frequency", once it was determined they were in reasonable walking distance to a public transit stop. This comment had value and led to discussions which referred to examples such as that highlighted in Figure 5.6, which shows a disused bus stop. Issues with data reliability were also discussed here. Although *Public Transport Access* gives some indication of origin to transit accessibility, dependent on data reliability, it does not explicitly indicate transitional or transit to destination accessibility. Therefore, this indicator would need further consideration. As one participant questioned, "should a local bus stop that does not provide access to [essential services such as] schools or hospitals be recorded as an accessible bus stop"?

Participants suggested that the *Government Investment* indicator was "very crude". The intention of this indicator was to provide an indication of the money going into transport infrastructure in a rural area but fails to address the specifics of what is being paid for and why. It was suggested that it would be more beneficial to specifically target road-based infrastructure spending, or to be explicit, target CAEV infrastructure and trial spending (although this data was not available). However, there were also discussions regarding investment prioritisation where it was suggested that if an area is receiving a lot of investment to fix problems, such as potholes, perhaps they could better prioritise the spending on adaptive, rather than mitigative measures. This supported the use of the original wide-scale investment figures used for the *Government Investment* indicator.

> *"The repair of a failed rail bridge could be expensive but not relevant to the topic … also costs are relative to place and so the money will buy less or more at certain locations."*

Supporting Planner Decision-Making

Participants were asked to what extent they believed the CARTI to be a useful tool to support transport planners in making rural CAEV implementation decisions. Whilst widely acknowledged as a "good start" in beginning the conversation around future vehicle technologies in rural areas, the CARTI itself was referred to as "limited" due to a suggested lack of indicators and therefore inability to cover a wider range of important transport aspects. One participant suggested that further development was needed and that the CARTI should be "considered more deeply against other variables" to compare the relative impact of its indicators. Further, it was suggested that the CARTI should somehow consider the integration of other transport modes, such as rail, given that the implementation of CAEVs is intended to promote multi-modal integration and public transport use.

Last-Mile Transport Solutions

There was an awareness of the importance of integrated transport solutions amongst professionals in the rail sector. In many cases, rail is seen as an effective transport solution for long distance and inter-city travel but often supporting last-mile transport solutions are needed to transport users from railway stations to their destinations. This is a particular challenge in rural areas, where the "last-mile" is often further than for those in urban areas and there are fewer last-mile transport options available.

If reinstated, the P&DL would present an opportunity to explore last-mile and integrated CAEV implementation, supported by railway infrastructure and station-based transport hubs. Rural CAEV trials in such scenarios could attempt to explore the impacts of CAEV implementation on rural accessibility, emissions and congestion.

> *"The reinstatement of the P&DL [would be] integrated with a comprehensive last mile network. [This] would allow a major re-adjustment in transport patterns … away from the car and towards public transport [reducing] surface transport emissions for both passenger and freight traffic."*

The workshop participants noted that, to promote healthy living and reduce transport emissions more quickly, last-mile solutions should favour active transport solutions, followed by zero-emission public transport including CAEV solutions, above the use of private ICE vehicles. However, there was concern that active travel would not be viable for many rural dwellers due to the typically large distances between rural destinations. As referenced during the workshops, there are currently many case studies emerging of new and carbon neutral last-mile transport solutions and technologies including park and rides, public e-bike and e-scooter services (O'Brien, 2021) and autonomous pods or taxis. However, it was noted that the majority of these were urban-based solutions that would not necessarily be viable in rural areas.

Integration with Rail

For the Derbyshire Dales case study, participants were asked to comment on how CAEVs and rail infrastructure and services could be effectively integrated and support one another.

Responses were generally limited and unoriginal with one participant suggesting a "joint booking system like Plus Bus where you buy onward travel as a package". This would be useful for rail users but would simply be applying an existing integration method to an alternative last-mile solution. In terms of supporting infrastructure, one participant suggested that rail stations could provide bespoke CAEV "parking and charging locations", however, again this already exists for private EVs and their users. In a shared and integrated CAEV transport system the need for parking should be reduced. In this case one suggestion could be that rail stations are used solely by CAEVs to pick-up and drop-off users and park to charge when necessary.

6.4 South Lakeland

South Lakeland is a local authority district in south Cumbria in the North West of England. Figure 6.4 shows South Lakeland and its position in the UK. Figure 6.4 highlights the major geographical overlaps with the Lake District National Park (LDNP). In the geographical centre of the South Lakeland and LDNP overlap sits Lake Windermere, the largest natural lake in England, which is a popular tourist destination for many local, national and international visitors to the region.

This case study explored the CARTI results for South Lakeland in the context of its location and rural characteristics. At this case study location, CAEV (in this case known as "driverless POD") trials have been taking place at the Brockhole site (Figure 6.4) owned and run by the Lake District National Park Authority (LDNPA) (LDNPA, 2021). This case study therefore explored the results of the POD trials and the potential use of the CARTI in relation to the successes of, and challenges faced, by the LDNPA PODs.

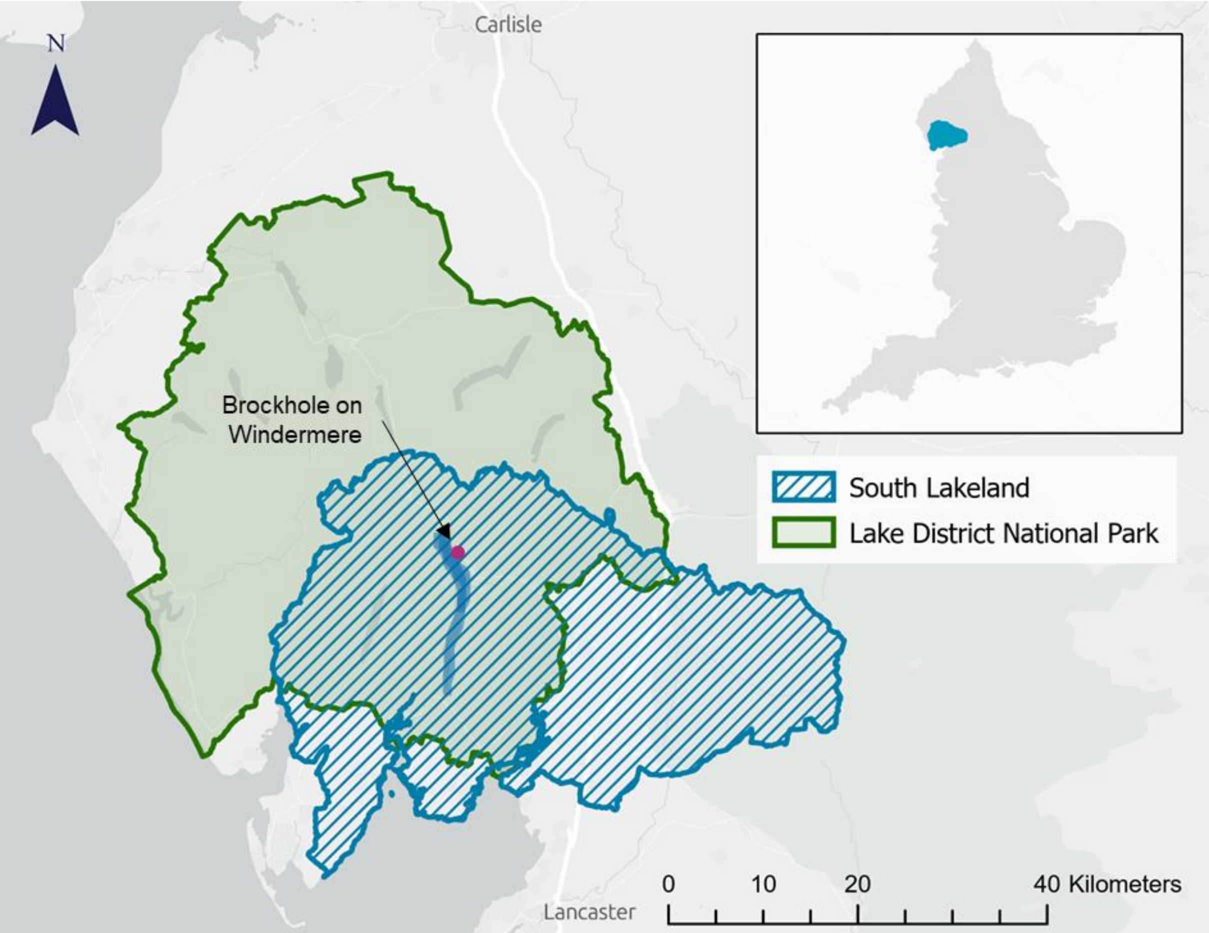


Figure 6.4 South Lakeland and location of Brockhole POD trials

Between 2019 and 2021 the LDNPA worked with Westfield Technology Group PODs (Pod on Demand) (Westfield, 2021) and Innovate UK to explore how CAEVs could offer residents and visitors an accessible and sustainable transport alternative. May 2021 saw the completion of the live POD trials at Brockhole (Figure 6.4), one of the first rural-based UK CAEV trials. The trials were part of the LDNPA vision for smarter travel, which in part aims to introduce and promote sustainable travel alternatives to private vehicle use and reduce the LDNP's carbon footprint, following a report on the LDNP's carbon and GHG emissions (Berners-Lee et al., 2017, LDNPA, 2018). The trials were conducted on private land owned by the LDNPA (Figure 6.5) but open to the public, who were asked to ride in and provide feedback on the PODs themselves, their use cases and to suggest any improvements (LDNPA, 2018).

The CARTI results (Table 6.2) indicate that South Lakeland struggles across every CARTI indicator and would need significant support to implement CAEV services. The lack of need also suggests there would be little demand for such solutions, although tourism demand is not accounted for. Therefore, whilst the CARTI suggests there are more appropriate alternative rural areas to carry out CAEV-trails than South Lakeland, the absence of tourism data limits the CARTI in being able to evaluate tourist hotspots such as the Lake and Peak districts effectively.

Figure 6.5 POD in operation at Brockhole on Windermere (Westfield, 2021: online)

6.4.1 Elicitation Results and Discussion

The validity, usefulness and application of the CARTI as well as the POD trials themselves were discussed with the Lead Strategy Adviser for Recreation and Sustainable Transport for the Lake District National Park Authority. The following section highlights the evaluative elements of the conversation regarding the

CARTI, potential relationships and links between the CARTI and POD trials and learnings from the POD trials that aligned or contradicted the findings contained within this thesis. The perspectives provided by the participant were based on their personal experience working in a rural transport environment and having recently completed CAEV trails in this environment. Whilst the participant recognised the value and relevance of each of the six CARTI indicators, a number of comments and suggestions were made regarding the data used and the specific indicators measuring *Emissions and Pollutants*, *Public Transport Spending*, *Public Transport Access* and *Internet Coverage*.

Tourism Data

Regarding the CARTI's use of publicly available data, which was ultimately based on static residential populations, the participant described some of the difficulties they had faced using this data when attempting to provide transport solutions for the large numbers of tourists who visit South Lakeland and the LDNP.

> *"One of the things that really complicates our data… across rural areas, is the volume of tourists that we receive. We've got 40,000 residents but every year we get nearly 20 million visitors."*

This was found to be a relevant comment, not just regarding the South Lakeland case study, but the Derbyshire Dales and Isles of Scilly case studies as well, given that both typically receive a substantial number of annual visitors compared to their resident populations. Considering the likelihood of the tourism sector being one of the early adopters of CAEV solutions, and with many UK tourist attractions in the UK being rural-based, the suggestion that that CARTI should incorporate "some kind of indicator as to the visitor need and the visitor capacity… [to integrate] across the needs or residents and of visitors" identified a shortcoming in the development and data processes of the creation of the CARTI, specifically for the selected case studies.

Emissions and Pollutants

Central to the reasoning behind conducting the POD trials was the challenge of rural carbon emissions. The participant explained that "the average rural dweller drives far more mileage and has a far greater carbon footprint than [urban dwellers] and we really have to tackle that." The participant supported the use of the *Emissions and Pollutants* indicator, particularly as it was measured per head of population, the results of which support the comment made. However, as with the modal shift and behavioural change challenges mentioned in the Derbyshire Dales case study, there was still uncertainty surrounding the willingness of travellers to switch transport mode. There was further uncertainty about whether personal concerns regarding emissions, the environment and climate change would be enough to encourage that switch. In terms of emissions and the environment, the participant was generally encouraged by the interactions they had with the people engaging with the POD trials.

> *"I was quite encouraged by the surveys and interactions we had with people. People are clearly very keen about something being done about reducing emissions, as you know climate change is much higher up the agenda than even it was a couple of years ago. I think a lot of people can see the problem but don't know the solution. A lot of people will say they are really concerned about climate change, but they still drive their cars because they don't know what else they can do. I do think people are open to suggestions."*

Public Transport Access

Regarding the accessibility of public transport, the participant noted that in rural areas in particular it was "really, really important that we provide something equitable" to people unable to drive, be that due to age, disability or financial circumstance. As such, being able to recognise and calculate the level of *Public Transport Access* was identified as an important component of the CARTI, particularly when considering these user groups. CAEVs are expected to play a key role in the implementation of on-demand shared transport solutions, of which the POD trial was an example, thereby expanding on traditional public transport methods such as buses and trains. Despite their zero-emission and long-term financial benefits, the participant was particularly concerned that "some people will just change their petrol car to an EV… and that's not the solution". They were concerned with congestion and cars "taking up space that could be better used for public realm or active travel". Shared transport solutions were therefore something that the participant was interested to see more of, having discussed "cars spending more than 90% of their time parked" and rural congestion challenges with the public during the POD trials. However, the participant believed that "some people are trapped in this car ownership" without suitable shared transport solutions whether they be autonomous or not. Therefore, the *Public Transport Access* indicator of the CARTI was seen as particularly useful to identify rural areas and communities in need of demand responsive and shared transport solutions.

Infrastructure

In terms of digital infrastructure and connectivity, the PODs tended to work well in the open but suffered when encountering trees both overhanging and as obstacles in relation to both inter-vehicle communications and satellite positioning. This supported the findings described in Chapter 3. Whilst the participant accepted the importance of "internet coverage as a key bit of infrastructure" as part of the CARTI, they were interested as to where the extent and quality of physical infrastructure could also be incorporated. Based on the POD trials conducted, the participant found that the PODs "struggle … to read where the edge of the road is" and find it "difficult" to navigate junctions. They also expressed concerns regarding the navigation and decision-making on "single track roads… whether to pull into the layby or when to reverse for the other car".

Referencing the experiments and findings in Chapter 3, physical infrastructure requirements were discussed at length. However, whilst the results in this thesis identified the potential need for well-maintained and consistent infrastructure, the impracticalities of such infrastructure in sparse rural areas were recognised. In addition, so too was the increasing reliance of automakers and technology developers on self-contained on-board sensor capabilities to enable CAEVs to navigate these challenging infrastructure scenarios.

Despite the Westfield Technology Group's advanced POD technologies, the participant found that the PODs "really struggled with any kind of bad road surface", including potholes and puddles. Whilst the participant accepted the unlikelihood of complete rural infrastructure investment and transformation to support the implementation of effective CAEVs, they still believed that current autonomous technologies were inadequate.

> *"You'll read the stuff about CAVs and that they're ready to go on the road, and all it needs is legislative changes, but I think the technology still needs a lot more development and refining."*

They suggested that there was a need for an additional CARTI indicator measuring road quality or consistency, although this is likely to be directly related to investment as measured by the *Government Investment* indicator.

> *"We have a huge number of road miles per inhabitant so investment is limited compared to an urban area… [physical] infrastructure is an additional thing that would need to be looked at."*

Usefulness

The reaction to whether the CARTI was a useful tool was generally positive, although the participant was hesitant with regards to the limited number of indicators used.

> *"I think [the CARTI] looks really good and obviously you've got to focus on certain indicators."*

The participant recognised that "urban [transport and CAEV] work tends to take priority because it's where the bulk of people live and where… the bulk of DfT funding is going" but stressed that "rural areas shouldn't be left behind." As such, the participant supported the idea of addressing of the urban transport and CAEV bias referred to throughout this thesis.

Reflecting on next steps following the POD trials, the participant recognised a need to identify locations for rural CAEV implementation based on levels of need. They stated that they "would want to focus on where [CAEVs] are needed and a tool like [the CARTI] would be really helpful particularly from the resident's side of things". The participant indicated that the CARTI was a useful contributor to the issue of rural implementation, however, they again questioned its usefulness in regard to recording and producing results relevant to tourists as well as residents. Further, they suggested that "area-wise it would be really useful to refine [the CARTI to identify] an area… in the National Park that would be the optimum place [for rural CAEV implementation]." Whilst this would be a useful next step in the CARTI's development, the participant also recognised the challenges associated with data availability at these smaller scales.

> *"In that case you would need smaller, more focused datasets and I don't know whether they're available in those areas, possibly not."*

In its current form the participant suggested that the CARTI would "be useful for the DfT if they were deciding about giving out grants" and also suggested using it as a transparent planning tool with a robust academic methodology behind it. They suggested the CARTI would help planners understand the reasoning behind DfT decision-making and recognise the justifications behind geographical-based decisions.

> *"Quite often you're not sure how these decisions are made by central government and there's a lot of discussion about levelling up funding and political bias in them… I feel it would be really good to have something like [the CARTI] showing the facts and the reasons for choosing those areas for the next set of trials. I could definitely see that being useful with a fair and scientific methodology behind it."*

Transport Planners

Regarding the state of transport planning and industry perceptions of CAEVs the participant supported the findings of this thesis, which identified an interest and willingness from transport planners regarding CAEV technologies and their implementation, but a lack of understanding and capacity to act.

The participant recognised that the CARTI had potential to be an important stepping-stone for transport planning authorities keen to engage with CAEVs and their rural implementation. However, the participant also noted that the present challenging planning climate may not be ready for such tools without improvements in staffing and investment.

> *"All local authorities have really suffered in terms of staffing and budget, so the exciting new stuff isn't the top priority when you're desperately trying to fill potholes in roads, or keep public buses going, or run school transport. There is a will, but people's day jobs get in the way".*

Public Perceptions of CAEVs

Although engaged in detailed conversation regarding the practicality of the CARTI, the participant struggled to directly relate this to their POD trial findings, as these focused more on education and public perceptions and engagement than the social, economic and infrastructural practicalities of CAEV implementation and location identification. Discussion regarding the public perceptions of the POD trials provided interesting insights, particularly regarding CAEV perceptions in the specifically rural LDNP scenario.

Although many studies highlighted in this thesis find the public sceptical about CAEVs and their implementation, the participant found that once "people had seen these vehicles and potentially ridden in them, they were much more confident about the safety aspects and how it could work". They felt that, because of the trials and its media coverage, local people were becoming more open to the new technology and "would welcome something different". The participant however did express concern regarding those they engaged with, saying that they tended to be technology oriented and partially interested in future transport solutions, rather than sceptics. As such, the feedback from the trials was unlikely to reflect the views of an average population sample.

Finally, the participant was optimistic about the impact of CAEV implementation on employment in rural areas. They explained that "rural areas have a lot of skills shortage in the workforce" and bus companies and hotels in the Lake District have been running reduced services due to a lack of staff. The participant identified CAEVs as a potential solution to this challenge, explaining that automated transport systems would reduce pressures on staffing so that businesses could worry less about transport and focus on other business areas.

> *"A few years ago, there were concerns about [CAEVs] taking away people's jobs, whereas now the bus company would think it's great because it helps deal with staffing shortage issues. So, there's certainly potential there."*

6.5 Isles of Scilly

The Isles of Scilly are a group of islands off the south-west coast of Cornwall, England and form a local authority district. Figure 6.6 shows the Isles of Scilly and its position in the UK. This case study explored the CARTI results for the Isles of Scilly in the context of its location and rural characteristics. Royal Mail has been conducting trials of autonomous unmanned aerial vehicles (UAV), or "drones", from Cornwall to and between the Isles (Brown, 2021, RMG, 2021). The initiative aimed to better connect the islands' remote communities to each other and mainland England. The initial advantages of using drones were their ability to fly in poor weather conditions such as fog, their independence from being unmanned and not being influenced by tides.

This case study explored these drone trials and the extent to which the CARTI could have influenced the trails and contributed to decision-making regarding aerial drone and ground-based delivery trials. The Isles are only accesibile by boat, plane or helicopter as there is no road access to or between the islands in the form of bridges or tunnels. The CARTI results (Table 6.2) indicate that the Isles of Scilly have the greatest capacity to support rural CAEV implementation in the UK, whilst need for such solutions is middling. The drone trails are strong evidence that the CARTI has effectively assessed the Isles of Scilly capacity to support CAEV technologies and implies road-based CAEV solutions could be effective in complimenting permanent drone deliveries.

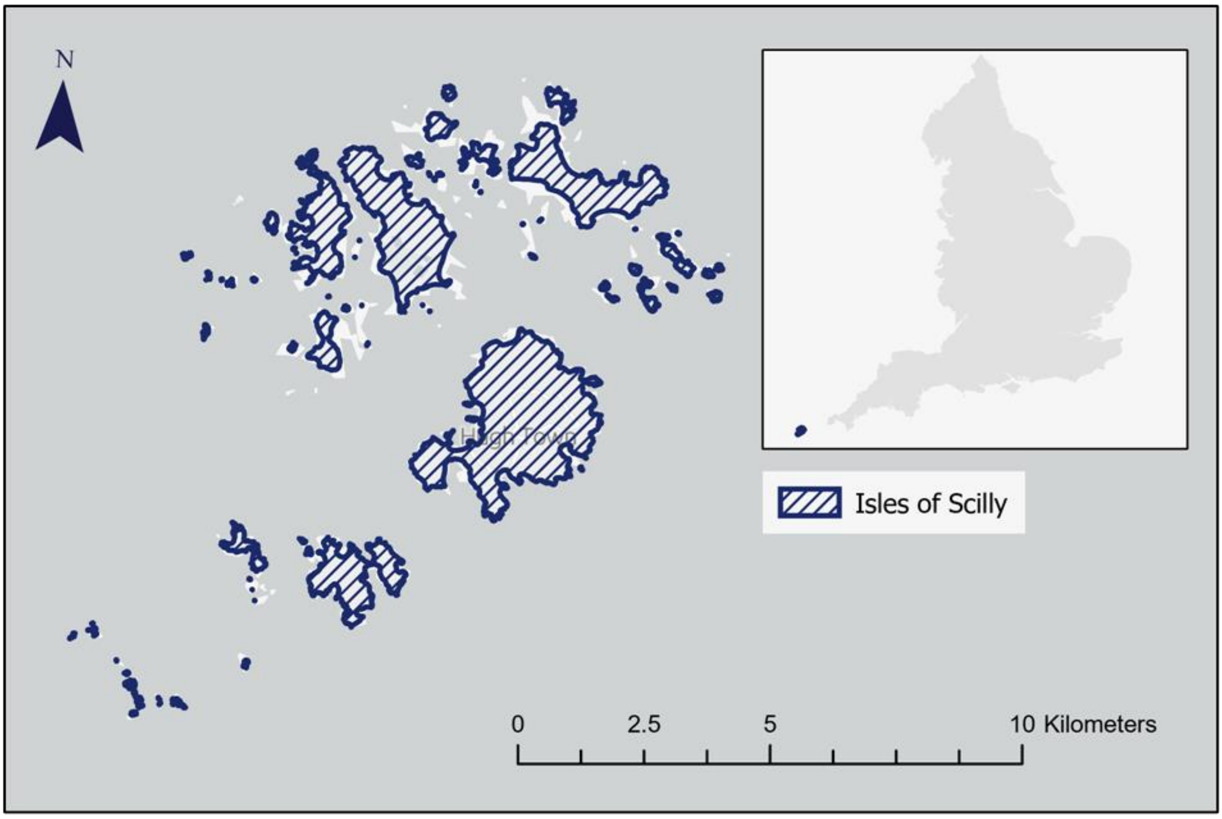


Figure 6.6 Isles of Scilly

The larger Windracers ULTRA UAV began delivering Personal Protective Equipment (PPE), COVID testing kits and more general mail to St. Mary's airport on the Isles of Scilly over the summer of 2020. This UAV was able to accommodate a variety of shapes and sizes of mail up to 100 kilograms at a time. The autonomous flight route involved approximately 70 miles out of sight before reaching its destination (Windracers, 2021). In addition to the large UAV, Royal Mail also explored inter-island parcel deliveries across the Isles of Scilly using a smaller drone manufactured by Swoop Aero and operated by Skyports capable of vertical take-off. This was used to transport items to a number of delivery points across the islands. The combination of these two drones demonstrated how drone types can complement, rather than compete with, each other (Brown, 2021).

During the trials, the drones were recognised as complementary technologies to existing delivery methods and acted to support, rather than replace, Royal Mail staff who delivered to very remote areas, often inaccessible by road. The trials have explored how innovative technologies are effectively implemented into existing transport networks without compromising but supporting existing industry jobs. In terms of the delivery industries specifically, which have seen huge increases in parcel volumes in recent years, effective and integrated autonomous vehicle implementation appears to be a feasible, convenient and green solution (Brown, 2021, RMG, 2021).

6.5.1 Elicitation Results and Discussion

The researcher was unable to conduct workshops with anyone directly involved in the drone delivery trials or any transport professionals on the Isles of Scilly. Despite this, some of the discussions with previous elicitation participants from both Chapter 4 and Chapter 6 were relevant to aerial autonomous drones, their requirements and the Isles of Scilly specifically. Further, the researcher has also engaged with the Scottish Rural and Islands Transport Community (SRITC) (Milne, 2020) and used some of their resources and recorded meetings to develop discussions around the use of CAEVs on remote rural islands.

Unique Island Challenges

Island communities face unique transport challenges. The Scottish Government Islands Team recognised this having engaged with the concerns raised by islanders across Scotland. Their strategic objective is to improve transport services by ensuring that existing and future transport-related policies, strategies and services are fully island proofed so that they truly meet the needs of island communities (Anson and Morrison, 2020).

> *"Transport was highlighted as one of the most important aspects of supporting sustainable island communities."*

Across islands in the UK, bus services are rarely commercially viable and private car travel is the dominant form of transport (Barton, 2020). This is exacerbated by a lack of pavements and safe active travel infrastructure on often old and poorly maintained roads. Of the bus services that do exist and are run by local authorities and councils, they are often limited in their frequency and their flexibility regarding origin and destination trips (King, 2020). Transport challenges extend to transport beyond island borders with limited access to the mainland often requiring trips either by boat or air. However, poor weather and a dependence on scheduling and human safety protocols limit services throughout the year (Barton, 2020).

> *"In the summer we find that sometimes the flights can't go because of a lot of fog so people have to use the boats, and in the winter, it can be quite choppy so people can't use the boat."*

One result of the dependence on private cars is a large carbon footprint per head of population for island inhabitants. For example, Shetland's carbon footprint is higher than the national average, and rather than falling, is getting higher (Barton, 2020).

However, these island-based transport challenges present opportunities for the development and implementation of low-carbon and demand-responsive CAEV solutions. The participant from the South Lakeland case study commented on the Isles of Scilly's uniqueness as a rural local authority. They explained that such island communities may have the most to gain from CAEV implementation particularly regarding the Isles' tourism sector as visitors rarely bring their own private vehicles across from the mainland.

> *"The Isles of Scilly is a really interesting [case study] because a lot of people get the boat across, and a lot of people won't actually take their car with them. There's a huge potential there and they've this huge benefit of being an island."*

Due to their isolation from the mainland and their reliance on traditional transport solutions there is an opportunity for a transformational shift in transport provision for such islands. Speaking specifically about the Orkney Isles in Scotland, Barton (2020) acknowledged the potential of CAEVs, referring in this case to MaaS as a transport solution, but identified the additional challenge of digital connectivity. A lack of digital connectivity is certainly the case on the Isles of Scilly, as the CARTI identified the Isles have a low *Internet Coverage* score compared to its other top scoring capacity-related indicators.

> *"Transport is very traditional (buses, planes and cars) so the whole world of MaaS is open to us in terms of different transport solutions to meet*

particular need but also looking at the digital journey planning aspects. [However], like many island places, we have the challenge of digital connectivity to grapple with."

The UAV Opportunity

Royal Mail have identified UAVs, an aerial form of CAEV, as a potential transport solution for mail deliveries to islands and continue to trial such technologies. There are a number of advantages to the use of UAVs, for island communities. Current human-piloted fixed winged aircraft are required to run on schedules which must consider the cost and safety of the people involved. However, autonomous aircraft allow the provision of on demand services and tailored flights. Also, improvements in UAV technology means that larger and greater quantities of deliveries will be possible as well as the transport of people via UAV (Buck, 2020).

"We're looking at going from kilograms of capability to tonnes of capability which allows [UAVs] to be more reactive to a developing [island] economy and more importantly bring that economy into out-of-hours so that you can improve sustainability and maintain the economy and culture."

UAVs are viewed as an important solution across UK island communities including those living in the Orkney Isles. Islands are also seen as ideal test beds to test such technologies. With UAVs being trialled, a natural evolution would be to introduce road-based CAEVs to deliver ground-based on-demand transport services. These would use similar technologies required to operate UAV delivery or passenger services. Similar challenges for UAV implementation exist as for road-based CAEV implementation including promoting the use of UAVs, determining the most effective methods with which to use and maintain UAVs, and integration with wider transport policies (Buck, 2020).

Islands can act as testbeds that are nice, closed environments separate from the mainland which allow you to look at the technologies and start using them in a commercialised way to meet the needs of people and specifically islanders.

A Rural Mobility Database

Rural island communities are small and have very specific needs unique to their individual geography and societies. Those that best understand island mobility and connectivity challenges and needs are therefore the islanders themselves. This case study into the Isles of Scilly, and more broadly rural islands, has identified the importance of such a resource and, whilst already mentioned on occasion in this thesis, has amplified the need for engagement with local communities to develop transport solutions.

To develop an effective transport solution and system, understanding from local perspectives on common issues, already tested and failed solutions, and data availability and quality are all important to identify gaps and be able to map rural demand for mobility services. Further, challenges and opportunities for rural island mobility aren't static, and solutions such as the CARTI require continual flows of data and community engagement (Forty Two, 2021).

> *"Some rural places have got a much better handle of data you can use to make planning decisions compared to others."*

However, the availability of data, particularly for rural areas is limited if not completely lacking, especially compared to urban areas. For the CARTI and other planning tools to be effective and dynamic, it is suggested that the rural data situation requires improvement. One solution is to develop a central rural data resource in the UK that could be used to collectively develop rural-specific mobility solutions; Innovation Nation is an example of such a project. A database like this would not only allow data to be shared and used, but also help to establish data collection and distribution techniques for rural areas currently lacking in this respect (Forty Two, 2021).

6.6 Case Study Conclusions and DfT Perspective

To summarise the local case study findings regarding the CARTI's potential usefulness for local decision-making, all three case studies identified a place for the CARTI to contribute to transport development. However, whether the methodology and selected indicators were appropriate remained a topic of debate. Whilst recognised as a "good start" in an important, but rarely discussed, area of transport development, the CARTI was also described as "limited" in its coverage of transport issues as well as geographic coverage. It was suggested that a smaller scale identifying specific cases for CAEV implementation would be more useful. There was, however, acknowledgement and understanding of the reasons behind selecting a limited number of indicators and the unavailability of data at smaller geographies. To support the case study conclusions, a final elicitation took place with the DfT's Chief Scientific Advisor to supplement the findings in this chapter from a national perspective.

The relevance and quantity of the selected CARTI indicators was debated with case study participants, having undergone a detailed assessment process described in Chapter 5, which also identified some potential shortcomings of the indicators. Whilst *Emissions and Pollutants*, *Internet Coverage*, and *Public Transport Access* were generally seen as realistic and relevant indicators to include, *Personal Transport Spending*, *Government Investment*, and *Market Share of EVs* were more heavily criticised. The Chief Scientific Advisor suggested that the measurement of *Personal Transport Spending* needed further review, citing expenditure on transport is more likely a sign of the extent of travel of a household, rather than the expense of their local transport systems. One suggestion could be to normalise this indicator further, using transport expenditure per mile in addition to expenditure as a proportion of household income. *Government Investment* was described as "crude" by a participant in the Derbyshire Dales case study, and this was echoed by the DfT's Chief Scientific Advisor who explained that the indicator was not specific enough about the areas of transport the investment was being spent on. To resolve this, whilst there is no specific investment category for CAEVs, individual categories of transport investment directly relevant to CAEV implementation could be selected and combined; however, this would require further investigation. Finally, *Market Share of EVs* was not directly criticised as an indicator of CAEV implementation potential, but it did generate the most discussion regarding alternative indicators. As described in the Derbyshire Dales case study, *Energy Capacity* was identified as a more useful indicator and references were made to the wider stability of charging infrastructure, rather than an indicator representing the number of EVs. In addition, the Chief Scientific Advisor suggested that *Market Share of EVs*, at this stage in the EV timeline, "might be more of a proxy for affluence", implying that once EVs were established as a mainstream solution, *Market Share of EVs* would become an increasingly relevant indicator. Further they explained that one of the most common talking points surrounding EVs was "whether people have off street parking or not and the charging issues associated with that". As such, they similarly suggested an indicator measuring charging network extent and capacity.

From a national perspective, the subject of the CARTI's usability was discussed. As a government department, the DfT is responsible for the policy and regulation that enables future transport technology implementation. The Chief Scientific Advisor suggested that there were two areas where an index such as the CARTI could be useful from a national policy decision-making perspective.

The first way in which the CARTI could be used was as an analytical approach to guide decisions regarding CAEV implementation. For each decision the DfT makes, a very detailed business case is produced, which in part looks at the wider economic benefits of that decision. As such, the CARTI would have to be developed or combined with a cost-benefit analysis accounting for many different factors not currently within the scope of the CARTI. They explained that there were "lots of really highly qualified analysts within the department who would want to look at [the CARTI] themselves and be confident that the answers being given are robust and subject to scrutiny".

The Chief Scientific Advisor added that it was "really important from a government point of view that decision-making is transparent, so having a good strong evidence base that enables and supports that decision making and therefore makes sure that that decision-making is fair and equitable is always very helpful". These comments supported those of the Lead Strategy Adviser for Recreation and

Sustainable Transport from the South Lakeland case study who suggested the CARTI with its "robust academic methodology behind it" could support DfT decision-making.

However, the second, and more likely, application of the CARTI that was suggested was its potential contribution to DfT strategies, such as the 2021 Transport Decarbonisation Plan (DfT, 2021c). The Chief Scientific Advisor explained that "many years of work feed into that transport decarbonisation strategy" including analysis and tools similar to the CARTI and its methodology. Further, once such strategies are in place, the DfT uses the components that contributed to the strategy to "support local authorities and other organisations in implementing solutions to help us to achieve the strategic targets set".

> *"What my policy colleagues will do is think of all of the levers that are available to stimulate the right level of market demand… so that there doesn't need to be any government intervention. The types of levers that are available are things like grants that are given to local authorities that help them to implement infrastructure [to] enable electric vehicle charging. Another lever is introducing secondary legislation which are targets or specifications that might stipulate something about the nature of the technology."*

From this perspective, the CARTI provides suggestions for "levers" under its capacity arm and could provide a method of monitoring progress regarding technology implementation strategies. For example, if a local authority was identified to have a poor *Government Investment* score, an economic boost from the DfT would improve this score and the CARTI could be used to monitor progress towards reducing the need orientated score, thereby improving the rural transport systems in that particular local authority. Again, this was supported by the comments made by the participant in the South Lakeland case study.

Following this discussion, the need for dynamicity became apparent. If the CARTI were to be useful over a long period of time to address the implementation of rural CAEVs in the UK, then the CARTI would need to analyse and model the state of local authorities and their transport systems as CAEV technologies are implemented at different times. From a DfT perspective, a dynamic CARTI would aid decisions regarding the "mix of policy and technology we might need to deliver against [strategy targets]". The needs for a dynamic CARTI were also reflected in the case studies where discussions included the integration of alternative and changing transport systems (rail, UAVs) and how people consider and use transport. For these reasons, it was suggested that "it would be really helpful to know how quickly things might change and [identify] real problems" over time.

From a national and DfT perspective, the Chief Scientific Advisor noted that the CARTI's most useful feature was its ability to identify specific local authorities and their attributes to aid DfT decision-making:

> *"What is then really helpful is working out for example which areas might benefit most effectively from different interventions. [The CARTI] will always ever only be one part of the decision-making process, in this [scenario] to determine regions where there is [CAEV implementation] potential."*

The Chief Scientific Advisor was keen to stress that the CARTI "would never be a sole decision-making tool because there will always be other factors and policies that interact". Examples of these included significant economic factors not addressed by the CARTI, the changing industry landscape of an area, political lobbying meaning that a particular area needs extra support and changing governance structures.

As explained by the South Lakeland case study participant, measuring factors relating to visitors and their needs is an area that the CARTI does not address but is a significant consideration for many rural areas and island communities. However, the integration of tourism data with the existing CARTI may not be the most effective solution. Alternatively, a new index could be developed focused specifically on rural tourism given the depth of data and volume of visitors travelling to rural locations in the UK. This would also provide a focus for the index and improve its potential usefulness for a specific sector, which is looking to address currently unsustainable transport models and systems as demonstrated by both the South Lakeland and Derbyshire Dales case studies in particular.

Finally, the Chief Scientific Advisor suggested that analytical tools used by the DfT need to be able to produce visually understandable results. This is something that they described that the CARTI would do well, particularly if it came in an interactive form (as it is as an ArcGIS file) that could be used by local authorities. To further improve the representation of the results, they suggested that the scores should be presented "in a much more discrete way". Figure 6.7 shows an updated CARTI (CAEV Potential) Score map based on this advice, which is easier for viewers to analyse and understand the major differences between local authorities.

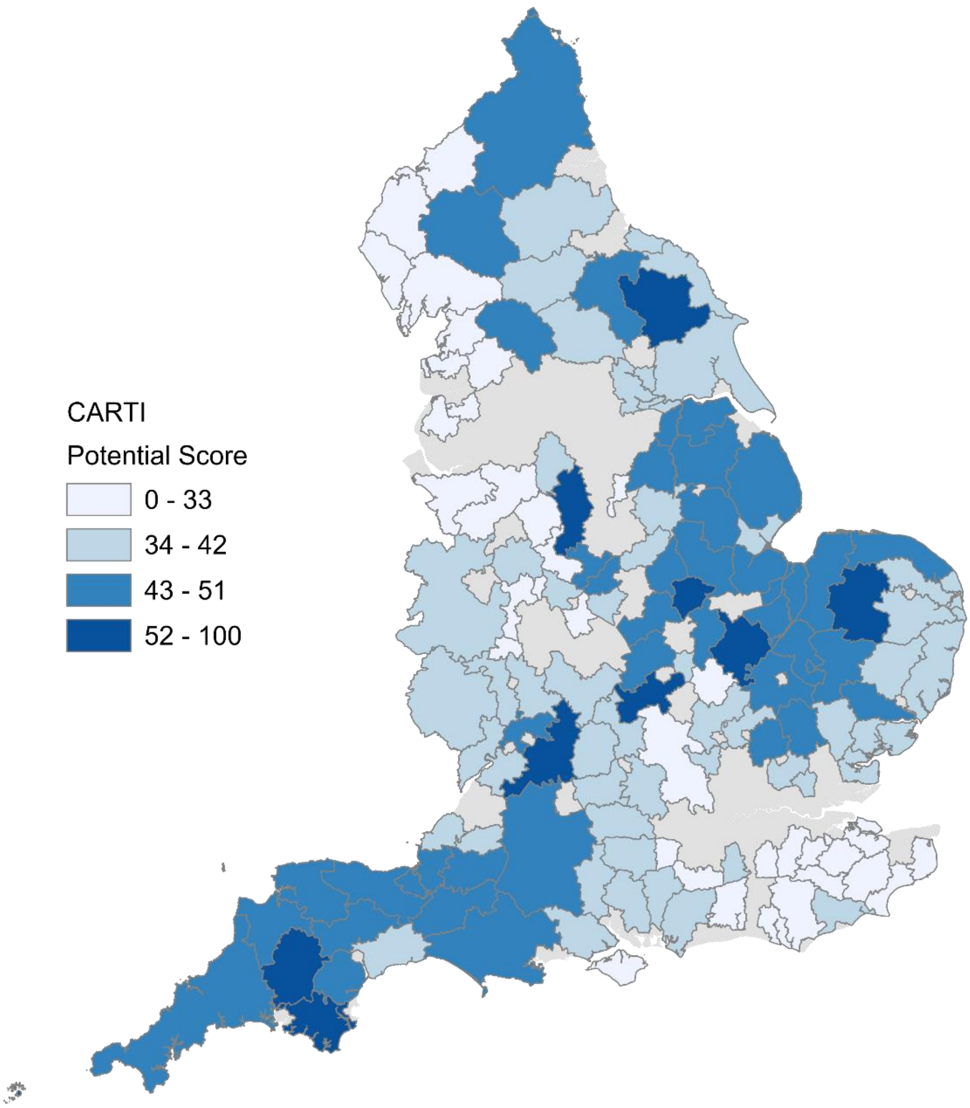


Figure 6.7 CARTI (CAEV Potential) Score, Discrete Natural Breaks

This chapter has reviewed how the CARTI could be applied to real case studies in England with critical reflections and recommendations made by local transport professionals and the DfT's Chief Scientific Advisor. Overall, the CARTI was found to be a useful concept with potential to make an impact in a rarely considered area of transport development. However, based on the comments recorded in this chapter, the CARTI would require further iterations and critical assessment before it could be used widely as a professional planning tool. The following chapter concludes this thesis, reflecting on the success of the studies leading up to the development of the CARTI and the application of the CARTI itself.

7 CONCLUSION

The chapters in this thesis have covered a range of research which supports the development and implementation of CAEVs in specifically rural areas. This final chapter summarises the author's perspectives on the research topic of rural CAEV implementation; evaluates the findings within this thesis by addressing the original thesis objectives; revises the contributions to knowledge made; identifies the major research limitations; and makes a number of recommendations and suggestions for further work. Based on the research conducted in this thesis, this concluding chapter starts below with the author detailing their perspectives on a strategy for rural CAEV implementation over the next ten years.

7.1 A Rural CAEV Implementation Strategy

To counteract currently urban biased CAEV development, rural CAEV implementation must be considered now, so that urban and rural CAEV solutions can be seamlessly integrated as they develop. This thesis, and the CARTI, significantly contribute to this much needed discussion. Given the current state of rural infrastructure to support CAEV implementation, the CARTI is a useful tool to identify opportunities to begin developing rural CAEV systems and solutions. However, to effectively optimise the process of CAEV implementation at larger scales, and bring opportunities level with urban developments, geographically consistent, reliable and high speed (4G minimum) wireless connectivity is fundamental. This can be supported by connected satellite solutions, including the use of low earth orbit (LEO) satellite technology, such as OneWeb and Starlink, which aim to provide improved digital connectivity to isolated geographic regions. In terms of physical infrastructure, the rollout of consistent roads, markings and signs is unlikely, given the wide geographical scale and associated high economic costs. However, rapidly improving CAEV sensing technologies will likely make the need for consistent physical infrastructure redundant. Despite this, there remains a need for rural-specific sensor trials to build up databases of physical infrastructure barriers and edge-cases to support sensor and CAEV software development.

Once digital communication and sensing capabilities are better established, tools such as the CARTI can be developed by transport planners to better focus on specific rural community needs and identify local CAEV solutions to address transport challenges. To do this, information regarding CAEV technology, its development, and potential must be shared through established knowledge exchange networks that bring together the wide range of CAEV industries and disciplines. This knowledge exchange would improve transport planners' understanding of CAEVs and give them the confidence to take a CAEV approach to rural transport challenges. Effective knowledge exchange also helps to simplify the development process into industry-specific stages; making CAEVs more manageable as a physical solution and less overwhelming technologically. Transport planners can be further supported through targeted government funding and rhetoric that focuses on transport efficiency through CAEV technologies, rather than "build back better" (HM Treasury, 2021) which implies a focus on expensive and outdated hard infrastructure.

Critical to this CAEV implementation strategy is regular engagement with local rural communities on their specific transport needs and challenges. This must be done at all levels of development and with every stakeholder in the multidisciplinary development chain, from hardware and software development to transport system planning, through to public use implementation. This will ensure that the technological solutions developed are adapted to specific rural community needs and conditions.

This strategy acts as a summarised conclusion to this thesis and brings together some of the major findings of this research. The following sections evaluate the specific elements of the research, including the original research objectives, and highlights some of the limitations of each chapter.

7.2 Research Aim and Objectives

The original aim of this thesis was to assess and promote the potential of CAEVs to contribute to sustainable rural transport development. Through a series of research stages, this aim was achieved by reviewing the potential for CAEVs to contribute to sustainable rural transport development; assessing the practicalities of the required CAEV implementation; and developing a planning tool to aid such implementation. Broken down, the research aim was achieved through the exploration of five individual research objectives. To evaluate these objectives, the findings associated with each objective will now be summarised and the extent to which each objective was fulfilled was assessed.

Objective A: Assess the Relationships between Rural Transport Development and CAEV Development within the Context of Sustainable Transport Development

Chapter 1 describes a literature review which explored the challenges of sustainable rural transport and identified accessibility, health and safety, economic incentives, transport emissions, and digital connectivity as barriers to sustainable rural development. The findings in Chapter 2 identified that the development of CAEV technologies and systems had the potential to address these specifically rural challenges through the implementation of CAEVs on rural roads designed to meet rural needs. Autonomous vehicle functions can provide improved accessibility options for those unable to drive or access a vehicle and they improve traffic safety through dynamic environmental sensing. Connected vehicle functions can help provide digital access to rural communities and improve traffic efficiency to reduce congestion and economic cost. Finally, battery electric functions reduce local GHG emissions to zero and can contribute to quieter and healthier communities. Therefore, Objective A has been addressed through identification and assessment of these links between rural transport challenges and the potential of CAEV technologies and systems.

Objective B: Determine to what extent the Needs of Rural Areas can be met by CAEV Systems and Technologies

As an extension of Objective A, this objective has also been addressed through the detailed literature review in Chapter 2, which described how CAEVs can contribute to the rural transport challenges of sustainable transport, accessibility, health and safety, efficiency, economics, the environment, and digital connectivity. In addition to the findings in Chapter 2, Chapter 4 introduced a research question to explore the extent to which transport planners believe that CAEVs were an important consideration for the future of rural sustainable transport systems. Planners are generally optimistic about rural CAEV implementation, believing that they are a sustainable solution to many of the rural transport needs identified, however, they have concerns about the cost of such solutions for both local government and the users. Therefore, the extent to which CAEVs have the potential to meet rural transport needs from both theoretical and professional perspectives has been assessed. However, further assessment of potential existing solutions and how they could be implemented into rural scenarios to meet rural transport needs would enrich the findings in this thesis to further meet this objective, and so they are a priority for further work.

Objective C: Identify the Practical Challenges of CAEV Implementation

Whilst a range of challenges were explored throughout the research, the practical digital and physical infrastructure challenges of rural CAEV implementation were explored in the greatest detail. Chapter 3 described a number of practical primary experiments which looked at the quality and reliability of digital and physical infrastructure in rural-based scenarios. Objective C was therefore achieved by identifying poor quality and inconstant rural road surfaces, markings and signposting; inconsistent and low-quality broadband and cellular internet coverage; lack of NRTK satellite positioning availability; and a lack of rural-based CAEV implementation trials and research. This achievement was enhanced through the additional challenges identified in Chapter 4 by transport and planning professionals, including: a lack of resources and time to sufficiently consider rural CAEV implementation; a lack of knowledge regarding CAEV technology and infrastructure requirements and the need for education and training; and a need for stronger interdisciplinary and cross-industry communication and collaboration.

Objective D: Set Out the Requirements for Rural CAEV Implementation where there is Distinguishable Need and Capacity

This objective relied on the success of the CARTI and its development described in Chapter 5 and applied in Chapter 6. Whilst the CARTI was used to assess a number of CAEV implementation requirements through the measurement of its indicators, these were by no means exhaustive. This is because the CARTI was designed to be a simple tool to maximise its potential use by transport planning professionals. Despite this, via the dual-index method, the CARTI does distinguish between a rural area's need and capacity to support CAEV implementation thereby, meeting this objective. In its current form, the CARTI sets out *Emissions and Pollutants*, *Personal Transport Spending*, and *Public Transport Access* as definitions which distinguish rural need for CAEV implementation; and *Market Share of EVs*, *Government Investment (in transport)*, and *Internet Coverage* as definitions which distinguish rural capacity to support CAEV implementation. The CARTI also highlighted some of the most important, although limited, indicators that reflected the requirements of both rural areas and CAEVs. Limitations of, and suggested further work, for the CARTI are described later in this chapter.

Objective E: Contribute to the Rural Implementation of CAEV Systems and Technologies

Through the literature reviews in Chapters 1 and 2, a gap was identified where CAEVs have the potential to meet many well-referenced rural transport and accessibility needs. This has created a foundation from which further studies can develop rural CAEV solutions to be implemented and therefore contributes to this objective. The practical experimentations in Chapter 3 identified technologies that would be effective for rural CAEV implementation, but also identified further challenges that these technologies are required to overcome. Therefore, this has further contributed to this objective.

In addition, Chapter 4 describes a study conducted of transport and planning professionals which has contributed to this objective in two ways. Firstly, the readiness of the planning industry to implement rural CAEVs was assessed and as a result some of the requirements needed to reach readiness identified. Secondly, through the elicitations, the professionals themselves gained a greater awareness of CAEVs as a solution to rural transport challenges. This, combined with the potential contribution of the CARTI as a transport planning tool described in Chapter 5 and 6, is the most influential impact that this thesis has on contributing to rural CAEV implementation and therefore this objective.

In summary, all objectives were at least partially met by this thesis. Work remains in order to further assess potential existing CAEV solutions and how they could be implemented to meet rural transport needs; apply the CARTI to a greater range of case studies and scenarios; and establish the research in this thesis as a basis for further study on the implementation of CAEVs in rural scenarios.

7.3 Contributions to Knowledge

This PhD thesis is an original piece of research which has contributed knowledge to the sustainable transport development research domain by investigating connected, autonomous and electric vehicle development and implementation in specifically rural contexts in the United Kingdom. This thesis comprises of four distinguishable sections that have contributed to knowledge, all four of which have been published as individual academic papers.

The first contributions to knowledge are the extensive literature reviews contained within Chapter 1 and Chapter 2, which explored rural transport challenges and the potential for CAEVs, and their technologies and implementation, to contribute to such challenges. This contribution has increased the awareness of CAEV solutions and their potential to meet rural transport needs from both public and professional perspectives.

Secondly, Chapter 3 has contributed scientific investigations into digital and physical CAEV technologies and transport infrastructure, including their rural-based capabilities and implementation requirements. Explicitly, Chapter 3 found that densely covered rural environments lack satellite positioning availability and that this, in combination with poor digital connectivity and poorly maintained road infrastructure suggests CAEVs are not yet viable in many rural road scenarios.

Thirdly, Chapter 4 has contributed to qualitative investigations into the state and readiness of the transport planning industry regarding rural CAEV implementation. It addressed the unique challenges facing the rural implementation of CAEV technologies, hard and soft supporting infrastructure, and stakeholder engagement and understanding explicitly, for the first time. It also demonstrated active engagement with transport planners to gather and contribute quantitative and qualitative evidence highlighting the extent of the gap in understanding and knowledge of CAEVs, their technologies and their rural transport potential.

Finally, Chapter 5 and 6 have highlighted the need to support transport planners in addressing the unique challenges facing the rural implementation of CAEV technologies, and the CARTI was offered as a novel solution to aid transport planner understanding and accelerate rural CAEV implementation. The CARTI's development has contributed a unique methodology which links the domains of transportation development, rural development and technological development together into a single sustain-ability-based future transport measurement index.

Finally, this thesis acts as a baseline from which further studies can develop future transport technology indexes to contribute to CAEV and other future transport solutions across the UK and globally.

7.4 Limitations

The limitations of this thesis are organised in terms of the contributions to knowledge outlined above and their respective chapters. The following research limitations identify some of the most significant potential limits of the research.

The researcher acknowledges that whilst extensive literature reviews were undertaken to form the foundation of this research they do not, and cannot, cover the entire extent of research in the field of interest. As this is a rapidly developing technological field, it is also the case that emerging and new research in the area will in some cases have been omitted. Therefore, the foundation for this research is strong but also has limits on its scope and coverage. As such, there is the potential for overlaps between the investigations carried out within this thesis and other unseen studies currently underway.

This research was also carried out over a period of four years, over which time there have been inevitable technological developments in the field. Whilst every effort has been made to keep the information in this thesis up to date, for some aspects of the research it is likely that more current research may supersede some that referenced or conducted in this thesis in the near future.

Whilst a highly accurate positioning method unique to the UK, the configuration of the NRTK GNSS receivers used in the experiment in Chapter 3 were restricted. This was because the NRTK receivers used were designed for geodetic measurement rather than for mobile use on road vehicles, resulting in a ten second age of correction limit. Despite this, the NRTK receivers were able to access the UK NRTK positioning service instantaneously, thereby reducing the impact of this limitation on the results. With newly developing mobile NRTK receivers it is recommended that further work includes rural road trails using these mobility-capable receivers to reinforce the findings in this area. In addition, the number of repeated routes were limited and therefore did not effectively represent a range of driving and infrastructure conditions.

Whilst this thesis explored NRTK positioning and V2X communication technologies separately, it is possible to combine them using a high precision GNSS V2X concept (Stephenson, 2016). However, it is noted that this is not the only method of delivering strong integrated positioning and communication performance for road vehicles. This is one example of a research limitation regarding the thoroughness of investigation into the integration of potential CAEV technologies. With further work, additional methods to effectively integrate the autonomous, connected and electric aspects of future vehicles could be reviewed. This would contribute further to scientific investigations into the relationships between integrated vehicle technologies and their surrounding infrastructure.

The major limitation in Chapter 4 was that the number of respondents to the elicitations were not statistically significant. In total there were 31 responses inclusive of interviews and surveys, three of which were from Canada. As such there are two associated limitations. Firstly, the number of UK responses was 28 so the number of perspectives were in some sense limited. Despite Figure 4.1 showing that the UK respondents were well distributed across rural regions, there would be a greater impact if there were more overall respondents, especially if some were from some of the most rural regions of the UK not covered by this research in Wales and the South West of England. Secondly, the three responses from Canada meant that only brief comparisons between UK and Canadian perspectives were appropriate. Ideally, the research would have collected a number of international perspectives on the issue. This limitation however opens up an opportunity for further study between CAEV ready nations (KPMG, 2019) and the potential to establish global perspectives and assess readiness for rural-specific CAEV implementation world-wide. CAEV implementation strategies will be different globally dependent on geographies and terrain, socio-economic structures and existing transport systems. For example, the CARTI in its current form could not be applied elsewhere due to international variations in in data types and availability. Despite this and likely adaptation requirements, the CARTI methodology would remain applicable internationally. In terms of the wider rural CAEV implementation strategy, the key themes of consistent digital and physical infrastructure, effective interdisciplinary knowledge exchange, and engagement with local communities would likely remain critical requirements for success.

There are several limitations associated with the development of the CARTI as a product of this research. Firstly, whilst the methodology is detailed, it ignores engagement with professionals mid-way through the development process as suggested by the ELASTIC methodology (Castillo and Pitfield, 2010), although this was a deliberate choice due to extensive engagement prior to and post CARTI development. However, the author suggests that future iterative processes of CARTI development should consider engaging professionals as ELASTIC suggests. Secondly, the measurement of each indicator was at a local authority level as a minimum. Through the application process this was found to be a limitation, given that one of the CARTI's intended purposes was to identify potential case study areas, which ideally needed to be a at village or road network level. However, easily accessible data was not available at these small geographic scales. Further, the number of indicators that made up the CARTI was considered small, thereby limiting the coverage of the measurement index and leaving out important aspects of rural and transport development, such as multi-modal integration. These will vary depending on transport planner perspectives and experience. Despite this potential limitation, it was well recorded in this thesis that the reason for the small number of indicators was to simplify the requirements and contributions of CAEVs for use by potentially overrun and under-resourced transport planners. It is also better to start simply, and then build complexity through consultation with professionals as this thesis has demonstrated. Therefore, using the methods in this thesis, the CARTI should be further developed iteratively to establish an effective balance of complexity and measurement coverage. Finally, whilst perspectives were recorded regarding the potential of the CARTI across the three case studies conducted by the author, the CARTI was not used by planners to implement CAEVs. This has left a gap which this research had intended to fill and therefore limits the impact of the CARTI at this stage. However, this leaves room for future development of this important tool that has resulted from this research.

7.5 Recommendations and Further Work

Chapter 3 of this thesis investigated some, but not all, of the infrastructure challenges facing CAEV implementation on rural roads, with the conclusion that, at present, there is a general lack of adequate supporting digital and physical infrastructure. Whilst there is a case for further work to be conducted regarding the specific quality and condition requirements for rural roads to be able to support CAEVs, with on-board sensor and mapping technologies improving at rapid rates, it is most likely that these will quash the need for consistent infrastructure. In fact, for rural areas, it is likely to be necessary for on-board technologies to eliminate the need for consistent and readable physical infrastructure, in which case further work into the technologies capable of achieving this and their thorough testing will be required.

Whilst the need for reliable physical infrastructure may be overcome by effective CAEV technologies, digital connectivity will always be a requirement and become more important as technologies develop, and over-the-air updates become commonplace. However, this thesis has found that connectivity is lacking on many rural roads and is a critical challenge that needs to be overcome for rural CAEV technologies to realise their full potential. Work to solve the infrastructure challenges identified in this thesis including V2X and GNSS positioning is already being undertaken. Further research into rural connectivity solutions is required. 5G connectivity for example offers impressive connectivity reliability and the speeds CAEVs are predicted to need, however, the terrestrial rollout of 5G is expected to be limited to densely populated urban areas. For wider coverage, one solution is the use of low earth orbit (LEO) satellites. These technologies are expected to provide global internet coverage which is indistinguishable between rural and urban areas. Whilst many of the infrastructure challenges found in this thesis are not new to the industry, the rural context in which they have been explored and uncovered is something rarely considered and something which needs to be addressed by upcoming UK CAEV development projects.

Whilst the professional elicitations in Chapter 4 and Chapter 6 of this thesis were by no means a thorough investigation of UK transport planner perspectives on the issue of rural CAEV implementation in the UK, they did begin to address the unique challenges facing rural implementation of CAEV technologies, hard and soft supporting infrastructure and stakeholder engagement and understanding. Further work on this topic would contribute to substantiating the results of this research study in the UK and extended research on the topic in other CAEV implementing countries is suggested.

Naturally, further study around the subject of rural CAEVs would look to identify areas in which rural-road and agricultural CAEV technologies could integrate and support each other. A second application, primarily discussed during the case studies, was that of rural tourism and the resulting need for shared and connected transport solutions to reduce local congestion and pollution. CAEVs have an important role to play in the futures of both rural agriculture and tourism applications. Such private and economically-driven applications would contribute to the required rural digital and satellite infrastructure improvements as highlighted in Chapter 3. These improvements would then support publicly-facing CAEV applications such as enhanced public transport services including autonomous shuttles, DRT and MaaS solutions for rural communities.

The CARTI needs to be tested more explicitly with further, more extensive workshops run to assess its application to real-world rural transport problems. In this case, an elicitation method such as protocol analysis as identified in 4.2 (Table 4.3) could be useful. It is in these scenarios that weaknesses of the CARTI could be specifically identified. The CARTI's indicator selection process selected a total of six indicators, three for each element. Through review of the selection stages, sensitivity analysis and case study application of these six indicators, it was determined that more indicators would likely be required, although this would be at odds with the goal to create a simple tool that in some ways needed further simplification. Following such analysis, the as-designed iterative approach of the CARTI's methodology could be utilised to develop the index by replacing less significant indicators or by adding or removing further indicators.

Throughout the CARTI's assessment, the need for further engagement was identified, whether that's with government, communities or industries such as tourism. Additionally, in its present form, the CARTI represents a snapshot of the rural transport situation in England regarding CAEV implementation and without a dynamic system in place to routinely update the CARTI's scores it is limited as to what it can achieve long term. Creating a dynamic CARTI with autonomous update features is recommended when taking the CARTI further.

Finally, the need for engagement between transport practitioners, researchers and the CAEV industry has been consistently identified at multiple levels. Practical action should be taken to ensure that rural communities do not lose out as they have historically done to urban-biased transport and technological development, in this case regarding CAEVs. This can be achieved through engagement with transport planning bodies and professionals, together with the development of methods to aid understanding and improve access to these technologies and their requirements, such as the CARTI. Such methods should encourage rural-based CAEV trials and implementation to enable effective technological rollout that specifically benefits and connects the rural communities they are intended to serve.

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APPENDIX A – PUBLICATIONS

Publications

Walters, J. G., Marsh, S., & Rodrigues, L. 2022. A Rural Transport Implementation Index for Connected, Autonomous and Electric Vehicles. *Future Transportation*, 2, 753.

Walters, J. G., Marsh, S., & Rodrigues, L. 2022. Planning Perspectives on Rural Connected, Autonomous and Electric Vehicle Implementation. *Sustainability,* 14, 1477.

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APPENDIX B – SURVEYS AND INTERVIEWS

Participant Information Sheet

Project title Future Rural Transport Planning

Researcher Joseph George Walters

Supervisors Stuart Marsh; Lucelia Rodrigues

Before you decide to take part in this study it is important that you understand why this research is being undertaken and what it involves. Please read the following information carefully. You may discuss it with others and your employer. After reading the information below please take the time to decide whether you wish to take part or not.

Project Information

Research into electric and connected and autonomous vehicles (CAV) is increasing and their technologies are developing at incredible rates. A growing number of road vehicles feature autonomous and connected capabilities that didn't exist 10 years ago. So far, our research has found that existing rural roads are unable to adequately support these emerging technologies and vehicles, especially when considering high-level autonomy and connectivity. This next research phase aims to determine the current state of rural transport planning and, considering emerging technologies such as CAVs, identify a future in which rural transport planning may be able to better support these technologies. This research also aims to determine whether the existing development indicators used to make planning decisions are applicable with the emerging technologies discussed.

Participant Selection and Participation

You have been selected as a participant due to your knowledge and experience in the transport planning sector in your region. We believe that your opinions and ideas about the topic described will be valuable to this research.

You may decide whether you would prefer to answer a written questionnaire or meet online for a one-to-one 30-minute interview. Participation in this study is entirely voluntary and you may refuse specific questions or withdraw from the study at your discretion. Please ensure that you read and understand this information sheet and sign the consent form before partaking in this study.

Contact

If you want to know more about taking part in this study, please contact either the researcher or their supervisors at the email addresses below.

Researcher: joseph.walters@nottingham.ac.uk

Supervisors: stuart.marsh@nottingham.ac.uk; lucelia.rodriguez@nottingham.ac.uk

Participant Consent Form

Study title Future Rural Transport Planning

Researcher Joseph George Walters

Supervisors Stuart Marsh; Lucelia Rodrigues

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I have read and understand the Participant Consent Form and Participant Privacy Notice below.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that while information gained during the study may be published, I will not be identified, and my personal results will remain confidential.
- I understand that, if I choose to take part in an online interview, the interview will be recorded.
- I understand that any responses I provide will be stored electronically in line with the University of Nottingham data protection guidelines. This data will be password protected and only accessible by the researcher. The researcher may share this data with their supervisors only.
- I understand that I may contact the researcher or supervisors if I require further information about the research.

Signed ………………………………………………………………………… (research participant)

Print name ………………………………………………………………… **Date** ………………………………………

Contact details

Researcher: joseph.walters@nottingham.ac.uk

Supervisors: stuart.marsh@nottingham.ac.uk; lucelia.rodriguez@nottingham.ac.uk

Participant Privacy Notice

Privacy information for Research Participants

For information about the University's obligations with respect to your data, who you can get in touch with and your rights as a data subject, please visit: https://www.nottingham.ac.uk/utilities/privacy.aspx.

Why we collect your personal data

We collect personal data under the terms of the University's Royal Charter in our capacity as a teaching and research body to advance education and learning. Specific purposes for data collection on this occasion are to identify your employer and the geographic region in which you work. Audio data will be recorded for transcription purposes.

Legal basis for processing your personal data under GDPR

The legal basis for processing your personal data on this occasion is Article 6(1a) consent of the data subject.

How long we keep your data

The University may store your data for up to 25 years and for a period of no less than 7 years after the research project finishes. The researchers who gathered or processed the data may also store the data indefinitely and reuse it in future research.

Who will use your data?

Measures to safeguard your stored data include the use of password protected UoN OneDrive folders which will only be accessible by the researcher until the end of the research project and shared only with their supervisors.

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator from a University of Nottingham email address or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name Joseph Walters

Reviewed by: D12

Date: 03/11/2020

■ Approval awarded - no changes required

☐ Approval awarded - subject to required changes (see comments below)

☐ Approval pending - further information & resubmission required (see comments)

☐ Approval declined – reasons given below

Comments:

Please note:

1. The approval only covers the participants and trials specified on the form and further approval must be requested for any repetition or extension to the investigation.
2. The approval covers the ethical requirements for the techniques and procedures described in the protocol but does not replace a safety or risk assessment.
3. Approval is not intended to convey any judgement on the quality of the research, experimental design or techniques.
4. Normally, all queries raised by reviewers should be addressed. In the case of conflicting or incomplete views, the ethics committee chair will review the comments and relay these to the applicant via email. All email correspondence related to the application must be copied to the Faculty research ethics administrator.

Any problems which arise during the course of the investigation must be reported to the Faculty Research Ethics Committee

Survey Question Schedule

Participant Information (* required)

2. In which country are you based? *

3. In which region or city is your work based? *

4.Who is your employer?

5. Briefly describe your job role. *

Rural Transport

6. Please rank the following priority areas for rural transport in your region, with the highest priority first.

   Accessibility
   Affordability
   Automation
   Communications infrastructure
   Environment quality
   Maintenance of infrastructure
   Public transport services
   Quality of infrastructure
   Safety
   Sustainability

7. To what extent do you agree that urban transport planning takes priority over rural transport planning?

   Strongly Disagree - 1 2 3 4 5 - Strongly Agree

8. To what extent do you agree that future transport systems and technologies are considered when planning rural transport systems and infrastructure?

   Strongly Disagree - 1 2 3 4 5 - Strongly Agree

Connected and Autonomous Vehicles

9. Are CAVs considered in rural transport planning in your region?
Yes
No
Sometimes
Don't know

10. To what extent are the following CAV supporting infrastructures considered in rural transport planning?

	Never	Rarely	Sometimes	Always
Electric charging infrastructure				
Machine-readable road features, markings, and signage				
Wireless communication networks				

11. Please rank the following barriers to rural CAV implementation, with the largest barrier to implementation first.

Communications infrastructure
Electric charging infrastructure
Industry acceptance
Machine-readable road features, marking and signage
Public acceptance
Regulation and law

12. To what extent do you agree that CAVs will improve the following aspects of rural transport?

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
Accessibility					
Affordability					
Environment quality					
Public transport services					
Safety					
Sustainability					

13. Please state any other areas of rural transport that you believe CAVs will improve.

CAVs in the Transport Planning Industry

14. In your opinion, how well are CAVs, their technologies, and their planning requirements understood amongst the rural transport planning industry?

Not understood - 1 2 3 4 5 - Completely understood

15. Please suggest how the understanding of CAV planning requirements could be improved?

The Proposed Research

This research project proposes to develop a simple set of indicators to aid rural transport planners in preparing for CAV implementation.

16. How useful do you believe such a set of indicators would be for rural transport planners?

    Not useful - 1 2 3 4 5 - Extremely useful

17. How useful would it be if these indicators were presented as a layered GIS that highlighted areas of need depending on their geographic indicator results?

    Not useful - 1 2 3 4 5 - Extremely useful

18. Finally, do you have any comments, thoughts, or suggestions regarding this research proposal?

Interview Question Schedule

Pre-interview

- Introductory email
- Send consent form, participant information sheet and data protection information
- Set a date and time
- Receive signed consent form
- Send link to Teams meeting

Start of interview

@ 0 minutes

- Welcome and thanks
- Explain interview process
    - I would like to record this interview, are you happy for me to do that?
    - Will take around 30 minutes, is there anywhere you need to be?
    - I'm happy for this to be a conversation so please ask questions at any time
- Start recording
- Confirm consent to conduct interview
- Confirm consent to record interview for transcription purposes
- Introduce interview topic - rural transport planning and the requirements for connected and autonomous vehicle implementation - focusing on rural implementation and road transport

Interview Questions

@ 3 minutes - About You and Rural Transport

1. Please can you tell me your job title and explain your job role (Q4,5)
2. Where is your work based or what geographic regions does your work cover? (Q2,3)
3. When thinking about rural transportation what are the priority areas, or problems that need to be addressed? (Q6)
4. There is an urban focus for CAV trials, do you think this is justified and why? Does this bias impact other aspects of transport? (Q7,8)

@ 10 minutes - About Rural CAV Implementation

5. Do transport planners consider CAVs and their infrastructure requirements when developing rural transport solutions? To what extent they are CAVs considered, and in what scenarios? (Q9,10)

6. What are the benefits of implementing CAVs on rural roads? How can these benefits be realised? (Q12,13)
7. Are there any barriers to rural CAV implementation? Are there strategies to overcome these? (Q11)

@ 20 minutes - Understanding of CAVs and Project Proposal

8. To what extent do transport planners understand CAVs and their technologies? What can or is anything being done to improve understanding? (Q14,15)
9. My research project proposes to develop a simple set of indicators to aid rural transport planners in preparing for CAV implementation. These indicators are to be visualised in a GIS to highlight specific areas that are lacking specific requirements for CAV implementation.
10. Do you have any thoughts to develop the research idea? (Q16,17)

End of Interview

@ 27 minutes

11. Do you have any questions or comments about the interview or my research?
12. Would you be willing to share an online survey with your networks that summarises the content of this interview?

- Thank you for your time and contribution. I will send you a transcript of this interview and I'm happy to share the results of other interviews and surveys.

Post-interview

- Thank you email with transcript
- Distribute survey

APPENDIX C – INDICATOR ANALYSIS

Longlisted Rural Transport and CAEV Indicators

Indicator	Description	Method	Author/Index
Air pollution	Transport emissions for air pollutants (NOX, MNVOCS, PM10, SOX, total ozone precursors) by mode/per passenger k exceeding EU air quality standards; emissions should not exceed 20% of 1990 levels; SuM4All C02 emissions relative to GDP in kg per $; proportion of vehicle fleet meeting air and noise emission standards; Transport-related GHG emissions per capita in tons of CO2 per capita - IEA; Total transport-related GHG emissions in million tonnes - IEA; Greenhouse gas emissions from transport; Transport emissions of greenhouse gasses (CO2 and N2O) by mode; particulate levels in air quality management areas; C02 emissions from road transport; N02 emissions per capita; NOx emissions per capita; total N0X emissions should not exceed 10% of total 1990 levels; O3 emissions per capita; Number of days ozone concentration exceeds 120 micrograms/m3 (days per year); A reduction of 55-99 percent of dine particulate emissions from transport; Number of days particulate matter concentrations (PM10) exceed 50 micrograms/m3 (days per year); PM10 and PM25 emissions per capita; Mean annual exposure to PM2.5 air pollution in micrograms per cubic meter - GBDS; Percentage of total population exposed to PM2.5 air pollution levels exceeding WHO guideline value - GBDS; SOX emissions per capita; VOC emissions per capita; Total emissions should not exceed 10 percent of total 1990 levels; Number of air quality management areas (AQMAs) on County Council managed roads		European Environment Agency x5; Regmi et al. (Asian Cities) x2; Pregl (JRC) x7; OECD 1999 x4; Sum4All x5; Nottinghamshire County Council x3; Zito and Salvo x2

Casualties	Number of road casualties and related changes (killed or injured); fatalities per vehicle/population; people slightly injured in road traffic collisions; people KSI; children KSI; Traffic accidents involving personal injury (number of injuries per 1000 vehicle km; per million inhabitants); Traffic fatalities per 100,000 people; Number of transport accidents, fatalities, injured, and polluting accidents (land, air and maritime); Persons killed in traffic accidents (number of fatalities per 1000 vehicle km; per million inhabitants); Number of deaths in road accidents per 10,000 population; Mortality caused by road traffic injury per 100,000 people - WHO; Attribution of road traffic deaths to alcohol (%) - WHO		OECD 1999 (total, vehicle, volume); world bank; Nottinghamshire County Council x3; Pregl (JRC) x2; Regmi et al.; European Environment Agency; Zito and Salvo; SuM4All x2
Density of Infrastructure	Land take by transport infrastructure by mode; compared to 1990 levels, this likely entails a smaller share of land devoted to transport; Total length of roads in km by mode; % of paved roads; road density in terms of land area (km/1000km2); road density in terms of population (km/1000 people); Length and density of road network in km per unit area giving an estimation of land use; Km of transport lines per km2; Proportion of Natura network area, the European ecological network of conservation areas; Density of infrastructure		Pregl (JRC Scientific) x3; European Environment Agency; OECD 1999 x2; World Bank x3; Michalek; Abreu
PT Access	Maximum acceptable walking distance to public transport is <650m urban; and <1300m rural and measured via safe pedestrian route; Transport nodes must provide regular services at least every 10/15 (peak/off-peak) minutes urban; every 30/60 minutes rural; Convenient access to public transport service; Rapid transit to resident ratio km per million people - ITDP; Average distance to nearest transport stop for rural population (km); Average distance to nearest transport stop for urban population (km); Accessibility to public transport services; number of fully accessible buses; Number of stops per km2		BREEAM Communities Technical Manual x2; Regmi et al.; SuM4All 2019; World Bank x2; Nottinghamshire County Council x2; Zito and Salvo
Road Quality	Condition of roads (fair/good, paved/unpaved); road quality from WEF Global Competitiveness Report; Quality of road score with 1 being worst and 7 best - WEF; % of roads in good condition; Condition of bridges and other structures; Principle A-roads where maintenance should be considered; Classified B-roads ""; Unclassified roads ""		Pregl (JRC Scientific); KPMG; SuM4All; World Bank; Nottinghamshire County Council x4
Personal Transport Spending	Spending on Transport Services by Urban/Rural household; Cost of a monthly ticket for public transport for 5-10km; Expenditure on personal mobility per person by income group; Real change in passenger transport price by mode; Travel costs as part of income; Direct user cost by mode (passenger transport)	% total expenditure	World Bank; Zito and Salvo; European Environment Agency x2; Regmi et al. (Asian cities); Pregl JRC Scientific x2
Consumption	Energy consumption by transport mode (tonne-oil equivalent per vehicle km); transport final and primary energy consumption by mode and fuel; overall energy efficiency for passenger and freight transport; Percentage of total fossil fuel energy consumption - IEA; use of renewable energy sources in transport; Uptake of cleaner fuels (unleaded petrol, electric, alternative fuels) and numbers of alternative-fuelled vehicles;		Pregl (JRC Scientific) x3; European Environment Agency x3; sum4all

Journey time/access	Average passenger journey time; Average journey time to work; Total time travelling by rural/urban households; Average passenger journey length per mode; Access to basic services: average passenger journey time and length per mode, purpose (commuting, shopping, leisure) and location (urban/ rural); Personal mobility (daily or annual person miles and trips by income group)	hours	Pregl (JRC Scientific) x3; Zito and Salvo 2011; World Bank; European Environment agency
Alternative transport	Number of alternative transport options (carpooling, cycle hire, lift sharing…); modal share of active and public transport in commuting; share of journeys to work by car (%); cycling levels		BREEAM Communities Technical Manual; Regmi et al.; Zito and Salvo; Nottinghamshire County Council
Noise	% of population exposed to and annoyed by traffic noise, by noise category and by mode; Proportion of vehicle fleet meeting certain air and noise emission standards (by mode); Population exposed to and annoyed by traffic noise, by noise category and by mode associated with health and other effects; 55-65 dB daytime; 45 dB night/indoors		European Environment Agency x2; Pregl (JRC); OECD 1999
Government investment	Investments in transport infrastructure/ per capita and by mode; Investment in public transport systems; Road expenditure as share of GDP; Investment in transport infrastructure (per capita by mode/as share of GDP)		European Environment Agency; Regmi et al.; World Bank; Pregl
Public Perception of PT	Public satisfaction with bus service; Bus services running on time; Public transport quality and reliability	survey	Nottinghamshire County Council x2; Regmi et al.
Vehicle Numbers	Number of registered cars per 1000 population; number of registered vehicles in thousands - WHO; Shift from road to rail, water and public passenger transport so that road transport share is no greater than that in 1998		Zito and Salvo 2011; SuM4All; EC 2005
LTP23/4 PT Information	Provision of information at bus stops; provision of real-time information		Nottinghamshire County Council x2
Passenger volume	Volume of passengers; Occupancy rates of passenger vehicles		Pregl (JRC Scientific); European Environment Agency
Active Transport Access	Level of access for pedestrians and cyclists; Length of shared or segregated cycle lane or path		CEEQUAL Technical Manual; Nottinghamshire County Council
Vehicle Ownership	Motorized Road Vehicle Ownership in Rural/Urban Areas: Private Cars/Motorcycles/Bicycles (% of rural households); Private car ownership		World Bank; Pregl (JRC)
4G Coverage	based on data from OpenSignal reflecting the importance of AV access to wide mobile data networks; Measure of mobile infrastructure assessed by GSM Association awarding availability of high-performance mobile internet network coverage, speed, servers, bandwidth…		KPMG x2
Ecosystem disruption	Habitat and ecosystem disruption; fragmentation of ecosystems (proximity of transport to designated areas)		Pregl (JRC Scientific); European Environment Agency
Population density	Number of people per square kilometre. The higher the value the "less isolated" the people are; number of people per square kilometre	people/km2	Abreu et al. (Portugal); Zito and Salvo

Rural Access Index	The percentage of rural people living within 2km (20 minute walk) of an all-season road as a proportion of rural population; Access to all season roads by rural population (% of total population)	rural pop within 2km / total rural pop	World Bank x2
Expenditure	Total per capita transport expenditures (parking, roads, transits services); expenditure for transport and communications (% of local budget	£/person	Pregl (JRC Scientific); Michalek 2013
External costs	Total amount of external costs by transport mode (freight and passenger); average external cost per passenger-km and tonne-km by transport mode; External costs of transport activities (congestion, emission, safety) by transport mode (passenger/freight)		European Environment Agency; Pregl (JRC)
LTP25	Take-up of concessionary fare passes		Nottinghamshire County Council
Road connectivity index	WEF index for road connectivity - score between 1 and 100 - WEF		SuM4All 2019
Rural Access Index	Rural Access Index Score as percentage - World Bank		SuM4All 2019
Transport quality	Quality of transport for disadvantaged people (disabled, low-income, children)		Pregl (JRC Scientific)
LTP2 (traffic miles)	Changes in area wide traffic milage (vehicle kilometres)	kilometres	Nottinghamshire County Council
Road traffic	Road traffic volumes and intensities and related changes over time in annual vehicle km, per capita, unit of GDP and road length		OECD 1999
Car Thefts	Car thefts in urban cities per 1000 people		Zito and Salvo 2011
Growth	Contribution of transport sector by mode to employment growth		Pregl (JRC Scientific)
Purchasing power	Purchasing power per capita with reference to the national value		Abreu et al. (Portugal)
Energy Transition Index	Energy transition index (%) - WEF		SuM4All 2025
Respiratory Disease	Cases of chronic respiratory diseases, cancer, headaches. Respiratory restricted activity days and premature deaths due to motor vehicle pollution		Pregl (JRC Scientific)
Capacity	Capacity of transport infrastructure networks, by mode and by type of infrastructure (motorway, national road, municipal road, etc.)		European Environment Agency
Charging Density	numbers of chargers scaled by length of paved roads; AV adoption requires EV charging infrastructure		KPMG
LTP11	Footways where maintenance should be considered		Nottinghamshire County Council
Maintenance expenditure	Actual to required road maintenance expenditure		World Bank
Plan Cover	Extent to which transport plans cover public transport, intermodal facilities and infrastructure for active modes		Regmi et al. (Asian cities)
Net migration	Measures an areas attractiveness by showing people moving from a place to another place	In - out	Abreu et al. (Portugal)
Ride Hailing	percentage of people who have used a ride-hailing service		KPMG
Technology adoption	availabilities of latest technologies, mobile subscriptions, internet access and bandwidth		KPMG

Technology use	overall technology use indicates potential for consumers to embrace AV		KPMG
Operational Cost	Operational cost of public transport		Regmi et al. (Asian cities)
Market share of EVs	Percentage of market that is EV - most AV will be EV, so market share is relevant		KPMG
Internalised costs	Internalisation of costs (implementation of economic policy tools with a direct link with the marginal external costs of the use of different transport modes)		Pregl (JRC Scientific)
Transport GDP	% of GDP contributed by transport		Pregl (JRC Scientific)
Transport volume	Volume of transport relative to GDP	ton/km; passenger/km	Pregl (JRC Scientific)

Indicator Groups

Theme	**Sub-Theme**	**Indicator**	**#**
Environmental	Pollution	Emissions and Pollutants	27
Social	Health and Safety	Casualties	12
Environmental	Spatial	Density of Infrastructure	11
Social	Accessibility	Public Transport Access	12
Economic	Infrastructure	Road Quality	8
Environmental	Energy	Consumption	7
Social	Transport Cost	Personal Transport Spending	7
Social	Accessibility	Journey time/access	6
Economic	Infrastructure	Government investment	7
Social	Accessibility	Alternative transport	4
Social	Health and Safety	Noise Pollution	4

Economic	Accessibility	Vehicle Ownership	5
Social	Health and Safety	Public Transport Quality	4
Economic	Infrastructure	Internet Coverage	2
Economic	Transport Cost	External costs	2
Environmental	Pollution	Ecosystem Disruption	2
Social	Accessibility	Public Transport Information	2
Social	Accessibility	Passenger volume	2
Social	Accessibility	Active Transport Access	2
Social	Spatial	Population density	2
Economic	Infrastructure	Capacity	1
Economic	Infrastructure	Charging Density	1
Economic	Maintenance	Active Transport Maintenance	1
Economic	Maintenance	Maintenance expenditure	1
Economic	Planning	Plan Cover	1
Economic	Spatial	Road traffic	3
Economic	Technology	Market share of EVs	1
Economic	Transport Cost	Operational Cost	1
Environmental	Energy	Energy Transition Index	1
Social	Accessibility	LTP25	1
Social	Accessibility	Road connectivity index	1
Social	Employment	Growth	1
Social	Health and Safety	Car Thefts	1
Social	Health and Safety	Respiratory Disease	1
Social	Spatial	Net migration	1
Social	Technology	Ride Hailing	1
Social	Technology	Technology adoption	1
Social	Technology	Technology use	1

CARTI Need Results and Scores

LAD20CD	LAD20NM	Region	RUCCD	RUCNM	CO2	PTS	PTA	CO2 Score	PTS Score	PTA Score	Need Score
E06000003	Redcar and Cleveland	North East	3	Urban with Significant Rural	1.454	15.701	0.000	34.206	85.317	0.000	39.841
E06000011	East Riding of Yorkshire	Yorkshire and The Humber	2	Largely Rural	1.828	15.547	9.456	44.379	66.119	28.686	46.394
E06000013	North Lincolnshire	Yorkshire and The Humber	3	Urban with Significant Rural	1.641	15.547	25.937	39.283	66.119	78.682	61.361
E06000017	Rutland	East Midlands	1	Mainly Rural	3.874	15.715	26.102	100.000	87.073	79.183	88.752
E06000019	Herefordshire, County of	West Midlands	2	Largely Rural	1.843	15.318	15.995	44.786	37.607	48.523	43.639
E06000022	Bath and North East Somerset	South West	3	Urban with Significant Rural	1.148	15.819	0.000	25.881	100.000	0.000	41.960
E06000024	North Somerset	South West	3	Urban with Significant Rural	1.290	15.819	2.260	29.744	100.000	6.857	45.534
E06000037	West Berkshire	South East	3	Urban with Significant Rural	1.984	15.336	8.719	48.599	39.826	26.451	38.292
E06000046	Isle of Wight	South East	1	Mainly Rural	0.829	15.336	1.819	17.201	39.826	5.520	20.849
E06000047	County Durham	North East	2	Largely Rural	1.366	15.701	7.542	31.803	85.317	22.880	46.667
E06000049	Cheshire East	North West	3	Urban with Significant Rural	1.507	15.016	4.185	35.643	0.000	12.696	16.113
E06000050	Cheshire West and Chester	North West	3	Urban with Significant Rural	1.658	15.016	4.185	39.735	0.000	12.696	17.477
E06000051	Shropshire	West Midlands	2	Largely Rural	1.819	15.318	7.542	44.112	37.607	22.880	34.866
E06000052	Cornwall	South West	1	Mainly Rural	1.800	15.819	14.943	43.609	100.000	45.331	62.980
E06000053	Isles of Scilly	South West	1	Mainly Rural	0.196	15.819	14.943	0.000	100.000	45.331	48.444
E06000054	Wiltshire	South West	2	Largely Rural	1.852	15.819	7.542	45.017	100.000	22.880	55.965
E06000055	Bedford	East of England	3	Urban with Significant Rural	1.621	15.676	4.280	38.749	82.123	12.985	44.619

E06000056	Central Bedfordshire	East of England	2	Largely Rural	1.465	15.676	7.542	34.494	82.123	22.880	46.499
E06000057	Northumberland	North East	2	Largely Rural	1.917	15.701	7.542	46.793	85.317	22.880	51.663
E06000059	Dorset	South West	2	Largely Rural	1.972	15.819	11.193	48.271	100.000	33.954	60.742
E06000060	Buckinghamshire	South East	3	Urban with Significant Rural	1.316	15.336	4.341	30.433	39.826	13.168	27.809
E07000009	East Cambridgeshire	East of England	1	Mainly Rural	2.860	15.676	6.926	72.427	82.123	21.010	58.520
E07000010	Fenland	East of England	2	Largely Rural	1.660	15.676	13.552	39.806	82.123	41.112	54.347
E07000011	Huntingdonshire	East of England	1	Mainly Rural	2.946	15.676	17.136	74.763	82.123	51.984	69.623
E07000012	South Cambridgeshire	East of England	2	Largely Rural	2.882	15.676	6.200	73.034	82.123	18.808	57.989
E07000026	Allerdale	North West	1	Mainly Rural	1.724	15.016	21.677	41.544	0.000	65.760	35.768
E07000027	Barrow-in-Furness	North West	3	Urban with Significant Rural	0.576	15.016	2.185	10.324	0.000	6.629	5.651
E07000028	Carlisle	North West	3	Urban with Significant Rural	1.334	15.016	12.535	30.939	0.000	38.028	22.989
E07000029	Copeland	North West	1	Mainly Rural	1.030	15.016	32.964	22.681	0.000	100.000	40.894
E07000030	Eden	North West	1	Mainly Rural	3.649	15.016	31.360	93.885	0.000	95.133	63.006
E07000031	South Lakeland	North West	1	Mainly Rural	2.220	15.016	21.167	55.022	0.000	64.212	39.745
E07000033	Bolsover	East Midlands	3	Urban with Significant Rural	1.247	15.715	3.174	28.566	87.073	9.630	41.756
E07000035	Derbyshire Dales	East Midlands	1	Mainly Rural	3.101	15.715	21.197	78.993	87.073	64.302	76.789
E07000037	High Peak	East Midlands	2	Largely Rural	1.643	15.715	0.000	39.346	87.073	0.000	42.140
E07000039	South Derbyshire	East Midlands	3	Urban with Significant Rural	2.707	15.715	7.421	68.268	87.073	22.512	59.284
E07000040	East Devon	South West	2	Largely Rural	1.604	15.819	11.767	38.288	100.000	35.697	57.995
E07000042	Mid Devon	South West	1	Mainly Rural	1.954	15.819	13.447	47.785	100.000	40.793	62.859
E07000043	North Devon	South West	2	Largely Rural	1.818	15.819	17.032	44.097	100.000	51.668	65.255
E07000044	South Hams	South West	1	Mainly Rural	2.655	15.819	22.111	66.852	100.000	67.077	77.976
E07000045	Teignbridge	South West	2	Largely Rural	2.823	15.819	10.222	71.433	100.000	31.010	67.481
E07000046	Torridge	South West	1	Mainly Rural	1.814	15.819	23.094	43.999	100.000	70.059	71.352
E07000047	West Devon	South West	1	Mainly Rural	3.227	15.819	15.410	82.406	100.000	46.748	76.385

E07000063	Lewes	South East	3	Urban with Significant Rural	1.605	15.336	0.000	38.300	39.826	0.000	26.042
E07000064	Rother	South East	2	Largely Rural	1.745	15.336	13.483	42.115	39.826	40.902	40.947
E07000065	Wealden	South East	1	Mainly Rural	2.065	15.336	7.400	50.806	39.826	22.448	37.693
E07000067	Braintree	East of England	2	Largely Rural	2.164	15.676	5.305	53.512	82.123	16.094	50.577
E07000068	Brentwood	East of England	3	Urban with Significant Rural	2.533	15.676	2.486	63.529	82.123	7.541	51.064
E07000071	Colchester	East of England	3	Urban with Significant Rural	1.743	15.676	1.296	42.059	82.123	3.930	42.704
E07000072	Epping Forest	East of England	3	Urban with Significant Rural	1.319	15.676	7.258	30.524	82.123	22.017	44.888
E07000074	Maldon	East of England	1	Mainly Rural	1.373	15.676	5.179	31.999	82.123	15.711	43.278
E07000076	Tendring	East of England	2	Largely Rural	1.579	15.676	0.997	37.609	82.123	3.024	40.919
E07000077	Uttlesford	East of England	1	Mainly Rural	2.451	15.676	5.325	61.301	82.123	16.153	53.192
E07000079	Cotswold	South West	1	Mainly Rural	3.125	15.819	18.059	79.638	100.000	54.785	78.141
E07000080	Forest of Dean	South West	1	Mainly Rural	1.554	15.819	4.168	36.915	100.000	12.645	49.853
E07000082	Stroud	South West	3	Urban with Significant Rural	1.326	15.819	2.664	30.724	100.000	8.082	46.269
E07000083	Tewkesbury	South West	2	Largely Rural	1.776	15.819	7.393	42.963	100.000	22.426	55.130
E07000084	Basingstoke and Deane	South East	3	Urban with Significant Rural	1.940	15.336	6.733	47.419	39.826	20.424	35.890
E07000085	East Hampshire	South East	1	Mainly Rural	2.515	15.336	6.215	63.051	39.826	18.853	40.577
E07000089	Hart	South East	3	Urban with Significant Rural	1.303	15.336	1.571	30.088	39.826	4.765	24.893
E07000091	New Forest	South East	3	Urban with Significant Rural	2.302	15.336	3.749	57.245	39.826	11.373	36.148
E07000093	Test Valley	South East	3	Urban with Significant Rural	2.484	15.336	6.923	62.214	39.826	21.001	41.014
E07000094	Winchester	South East	2	Largely Rural	2.157	15.336	6.549	53.324	39.826	19.868	37.673
E07000096	Dacorum	East of England	3	Urban with Significant Rural	1.375	15.676	0.000	32.038	82.123	0.000	38.054
E07000099	North Hertfordshire	East of England	3	Urban with Significant Rural	1.612	15.676	5.375	38.497	82.123	16.307	45.642

E07000105	Ashford	South East	3	Urban with Significant Rural	1.327	15.336	2.060	30.747	39.826	6.249	25.607
E07000108	Dover	South East	3	Urban with Significant Rural	1.315	15.336	1.677	30.408	39.826	5.089	25.108
E07000110	Maidstone	South East	3	Urban with Significant Rural	1.161	15.336	4.219	26.228	39.826	12.800	26.285
E07000111	Sevenoaks	South East	2	Largely Rural	1.375	15.336	3.323	32.051	39.826	10.081	27.320
E07000112	Folkestone and Hythe	South East	3	Urban with Significant Rural	1.112	15.336	1.812	24.909	39.826	5.496	23.410
E07000113	Swale	South East	2	Largely Rural	1.364	15.336	5.118	31.747	39.826	15.526	29.033
E07000115	Tonbridge and Malling	South East	3	Urban with Significant Rural	1.485	15.336	0.000	35.032	39.826	0.000	24.953
E07000116	Tunbridge Wells	South East	3	Urban with Significant Rural	1.343	15.336	3.144	31.169	39.826	9.539	26.845
E07000118	Chorley	North West	3	Urban with Significant Rural	0.905	15.016	0.000	19.267	0.000	0.000	6.422
E07000121	Lancaster	North West	3	Urban with Significant Rural	1.295	15.016	3.617	29.886	0.000	10.972	13.619
E07000124	Ribble Valley	North West	1	Mainly Rural	1.938	15.016	6.992	47.367	0.000	21.212	22.860
E07000127	West Lancashire	North West	3	Urban with Significant Rural	1.413	15.016	1.797	33.081	0.000	5.453	12.844
E07000128	Wyre	North West	2	Largely Rural	1.238	15.016	9.932	28.316	0.000	30.130	19.482
E07000131	Harborough	East Midlands	1	Mainly Rural	1.684	15.715	17.543	40.457	87.073	53.219	60.249
E07000132	Hinckley and Bosworth	East Midlands	2	Largely Rural	1.411	15.715	4.355	33.034	87.073	13.211	44.439
E07000133	Melton	East Midlands	1	Mainly Rural	2.133	15.715	19.903	52.652	87.073	60.378	66.701
E07000134	North West Leicestershire	East Midlands	2	Largely Rural	2.739	15.715	6.396	69.134	87.073	19.404	58.537
E07000136	Boston	East Midlands	3	Urban with Significant Rural	1.630	15.715	11.539	38.985	87.073	35.005	53.688
E07000137	East Lindsey	East Midlands	1	Mainly Rural	1.898	15.715	23.597	46.266	87.073	71.585	68.308
E07000139	North Kesteven	East Midlands	1	Mainly Rural	1.964	15.715	17.483	48.071	87.073	53.037	62.727
E07000140	South Holland	East Midlands	2	Largely Rural	1.920	15.715	25.122	46.858	87.073	76.210	70.047

E07000141	South Kesteven	East Midlands	2	Largely Rural	2.302	15.715	14.857	57.244	87.073	45.071	63.129
E07000142	West Lindsey	East Midlands	1	Mainly Rural	2.177	15.715	14.943	53.857	87.073	45.331	62.087
E07000143	Breckland	East of England	1	Mainly Rural	2.567	15.676	21.523	64.462	82.123	65.292	70.626
E07000144	Broadland	East of England	3	Urban with Significant Rural	1.728	15.676	7.104	41.657	82.123	21.552	48.444
E07000145	Great Yarmouth	East of England	3	Urban with Significant Rural	1.145	15.676	2.386	25.807	82.123	7.239	38.390
E07000146	King's Lynn and West Norfolk	East of England	2	Largely Rural	2.353	15.676	15.013	58.646	82.123	45.545	62.105
E07000147	North Norfolk	East of England	1	Mainly Rural	1.757	15.676	21.933	42.440	82.123	66.536	63.700
E07000149	South Norfolk	East of England	1	Mainly Rural	2.579	15.676	11.973	64.799	82.123	36.321	61.081
E07000151	Daventry	East Midlands	1	Mainly Rural	3.141	15.715	13.810	80.062	87.073	41.895	69.677
E07000152	East Northamptonshire	East Midlands	2	Largely Rural	2.337	15.715	15.793	58.206	87.073	47.910	64.396
E07000155	South Northamptonshire	East Midlands	1	Mainly Rural	3.016	15.715	23.738	76.676	87.073	72.013	78.587
E07000156	Wellingborough	East Midlands	3	Urban with Significant Rural	1.782	15.715	6.718	43.105	87.073	20.381	50.186
E07000163	Craven	Yorkshire and The Humber	1	Mainly Rural	2.258	15.547	15.086	56.066	66.119	45.765	55.983
E07000164	Hambleton	Yorkshire and The Humber	1	Mainly Rural	3.142	15.547	20.188	80.104	66.119	61.242	69.155
E07000165	Harrogate	Yorkshire and The Humber	3	Urban with Significant Rural	1.575	15.547	13.433	37.491	66.119	40.750	48.120
E07000166	Richmondshire	Yorkshire and The Humber	1	Mainly Rural	2.062	15.547	9.192	50.739	66.119	27.885	48.248
E07000167	Ryedale	Yorkshire and The Humber	1	Mainly Rural	3.371	15.547	24.309	86.319	66.119	73.745	75.394
E07000168	Scarborough	Yorkshire and The Humber	3	Urban with Significant Rural	1.291	15.547	5.309	29.756	66.119	16.106	37.327
E07000169	Selby	Yorkshire and The Humber	1	Mainly Rural	2.117	15.547	8.143	52.219	66.119	24.703	47.680
E07000171	Bassetlaw	East Midlands	2	Largely Rural	2.664	15.715	7.542	67.111	87.073	22.880	59.021
E07000175	Newark and Sherwood	East Midlands	2	Largely Rural	3.154	15.715	14.929	80.422	87.073	45.290	70.928
E07000176	Rushcliffe	East Midlands	2	Largely Rural	2.129	15.715	5.216	52.556	87.073	15.823	51.817
E07000177	Cherwell	South East	3	Urban with Significant Rural	2.060	15.336	12.150	50.681	39.826	36.860	42.456

E07000179	South Oxfordshire	South East	1	Mainly Rural	1.447	15.336	7.066	33.996	39.826	21.436	31.753
E07000180	Vale of White Horse	South East	2	Largely Rural	2.599	15.336	8.543	65.318	39.826	25.915	43.686
E07000181	West Oxfordshire	South East	1	Mainly Rural	1.693	15.336	8.875	40.687	39.826	26.925	35.813
E07000187	Mendip	South West	1	Mainly Rural	1.992	15.819	10.472	48.822	100.000	31.769	60.197
E07000188	Sedgemoor	South West	2	Largely Rural	1.604	15.819	8.545	38.273	100.000	25.921	54.731
E07000189	South Somerset	South West	2	Largely Rural	2.130	15.819	9.832	52.591	100.000	29.826	60.806
E07000192	Cannock Chase	West Midlands	3	Urban with Significant Rural	0.857	15.318	0.000	17.966	37.607	0.000	18.524
E07000193	East Staffordshire	West Midlands	3	Urban with Significant Rural	1.839	15.318	5.397	44.658	37.607	16.372	32.879
E07000194	Lichfield	West Midlands	3	Urban with Significant Rural	2.532	15.318	12.333	63.503	37.607	37.413	46.174
E07000196	South Staffordshire	West Midlands	3	Urban with Significant Rural	1.480	15.318	6.489	34.891	37.607	19.686	30.728
E07000197	Stafford	West Midlands	3	Urban with Significant Rural	1.505	15.318	10.866	35.591	37.607	32.962	35.387
E07000198	Staffordshire Moorlands	West Midlands	2	Largely Rural	1.764	15.318	9.882	42.639	37.607	29.980	36.742
E07000200	Babergh	East of England	1	Mainly Rural	2.491	15.676	14.168	62.385	82.123	42.981	62.497
E07000203	Mid Suffolk	East of England	1	Mainly Rural	2.648	15.676	20.622	66.655	82.123	62.560	70.446
E07000210	Mole Valley	South East	3	Urban with Significant Rural	1.658	15.336	2.175	39.739	39.826	6.598	28.721
E07000215	Tandridge	South East	3	Urban with Significant Rural	1.413	15.336	3.292	33.082	39.826	9.987	27.632
E07000216	Waverley	South East	2	Largely Rural	1.954	15.336	3.468	47.790	39.826	10.521	32.712
E07000218	North Warwickshire	West Midlands	1	Mainly Rural	2.243	15.318	7.613	55.652	37.607	23.096	38.785
E07000221	Stratford-on-Avon	West Midlands	1	Mainly Rural	2.273	15.318	9.732	56.466	37.607	29.522	41.199
E07000225	Chichester	South East	2	Largely Rural	2.447	15.336	7.045	61.203	39.826	21.371	40.800
E07000227	Horsham	South East	2	Largely Rural	1.983	15.336	2.244	48.574	39.826	6.809	31.736
E07000235	Malvern Hills	West Midlands	2	Largely Rural	1.915	15.318	9.184	46.734	37.607	27.860	37.400
E07000238	Wychavon	West Midlands	1	Mainly Rural	1.803	15.318	5.973	43.698	37.607	18.121	33.142
E07000239	Wyre Forest	West Midlands	3	Urban with Significant Rural	1.269	15.318	3.037	29.176	37.607	9.214	25.332

E07000242	East Hertfordshire	East of England	3	Urban with Significant Rural	1.811	15.676	10.585	43.908	82.123	32.110	52.714
E07000244	East Suffolk	East of England	2	Largely Rural	1.559	15.676	10.239	37.047	82.123	31.062	50.077
E07000245	West Suffolk	East of England	2	Largely Rural	2.357	15.676	7.456	58.763	82.123	22.619	54.502
E07000246	Somerset West and Taunton	South West	2	Largely Rural	1.838	15.819	13.153	44.636	100.000	39.900	61.512

CARTI Capacity Results and Scores

LAD20CD	LAD20NM	Region	RUCCD	RUCNM	BEV	4G	Investment	BEV Score	4G Score	Investment Score	Capacity Score
E06000003	Redcar and Cleveland	North East	3	Urban with Significant Rural	0.180	100.000	111.275	0.000	100.000	13.054	37.685
E06000011	East Riding of Yorkshire	Yorkshire and The Humber	2	Largely Rural	0.285	97.900	80.463	1.349	92.545	9.418	34.437
E06000013	North Lincolnshire	Yorkshire and The Humber	3	Urban with Significant Rural	0.256	96.470	62.004	0.978	87.469	7.240	31.896
E06000017	Rutland	East Midlands	1	Mainly Rural	0.569	99.850	88.522	5.000	99.468	10.369	38.279
E06000019	Herefordshire, County of	West Midlands	2	Largely Rural	0.517	95.290	95.463	4.330	83.280	11.188	32.933
E06000022	Bath and North East Somerset	South West	3	Urban with Significant Rural	0.811	96.590	85.798	8.100	87.895	10.047	35.347
E06000024	North Somerset	South West	3	Urban with Significant Rural	0.633	96.120	71.177	5.820	86.226	8.322	33.456
E06000037	West Berkshire	South East	3	Urban with Significant Rural	0.730	98.630	64.033	7.062	95.137	7.479	36.559
E06000046	Isle of Wight	South East	1	Mainly Rural	0.459	100.000	131.641	3.593	100.000	15.457	39.683

E06000047	County Durham	North East	2	Largely Rural	0.313	100.000	91.941	1.710	100.000	10.772	37.494
E06000049	Cheshire East	North West	3	Urban with Significant Rural	0.569	97.830	72.225	5.000	92.297	8.446	35.248
E06000050	Cheshire West and Chester	North West	3	Urban with Significant Rural	0.463	95.040	74.794	3.640	82.393	8.749	31.594
E06000051	Shropshire	West Midlands	2	Largely Rural	0.440	96.060	104.190	3.337	86.013	12.218	33.856
E06000052	Cornwall	South West	1	Mainly Rural	0.455	98.500	91.990	3.537	94.675	10.778	36.330
E06000053	Isles of Scilly	South West	1	Mainly Rural	7.970	92.830	848.158	100.000	74.547	100.000	91.516
E06000054	Wiltshire	South West	2	Largely Rural	1.611	95.420	70.191	18.375	83.742	8.206	36.774
E06000055	Bedford	East of England	3	Urban with Significant Rural	0.576	80.060	107.152	5.091	29.215	12.567	15.625
E06000056	Central Bedfordshire	East of England	2	Largely Rural	0.623	95.620	59.980	5.687	84.452	7.001	32.380
E06000057	Northumberland	North East	2	Largely Rural	0.490	98.040	130.072	3.986	93.042	15.271	37.433
E06000059	Dorset	South West	2	Largely Rural	0.543	93.460	137.349	4.668	76.784	16.130	32.527
E06000060	Buckinghamshire	South East	3	Urban with Significant Rural	0.930	98.890	11.125	9.636	96.060	1.237	35.644
E07000009	East Cambridgeshire	East of England	1	Mainly Rural	0.577	100.000	1.397	5.100	100.000	0.089	35.063
E07000010	Fenland	East of England	2	Largely Rural	0.230	99.390	8.964	0.650	97.835	0.982	33.155
E07000011	Huntingdonshire	East of England	1	Mainly Rural	0.597	100.000	8.492	5.364	100.000	0.926	35.430
E07000012	South Cambridgeshire	East of England	2	Largely Rural	0.881	94.110	7.489	9.004	79.091	0.808	29.634
E07000026	Allerdale	North West	1	Mainly Rural	0.218	92.190	19.196	0.493	72.275	2.189	24.986
E07000027	Barrow-in-Furness	North West	3	Urban with Significant Rural	0.193	98.570	15.211	0.168	94.924	1.719	32.270
E07000028	Carlisle	North West	3	Urban with Significant Rural	0.255	98.300	13.969	0.965	93.965	1.572	32.167
E07000029	Copeland	North West	1	Mainly Rural	0.210	87.510	7.672	0.387	55.662	0.829	18.959
E07000030	Eden	North West	1	Mainly Rural	0.335	99.280	3.367	1.991	97.444	0.321	33.252
E07000031	South Lakeland	North West	1	Mainly Rural	0.509	91.000	29.169	4.235	68.051	3.366	25.217
E07000033	Bolsover	East Midlands	3	Urban with Significant Rural	0.235	86.760	3.960	0.714	53.000	0.391	18.035

E07000035	Derbyshire Dales	East Midlands	1	Mainly Rural	0.556	99.550	16.929	4.835	98.403	1.921	35.053
E07000037	High Peak	East Midlands	2	Largely Rural	0.431	100.000	5.786	3.226	100.000	0.607	34.611
E07000039	South Derbyshire	East Midlands	3	Urban with Significant Rural	0.361	100.000	3.296	2.325	100.000	0.313	34.213
E07000040	East Devon	South West	2	Largely Rural	0.508	86.870	8.408	4.220	53.390	0.916	19.509
E07000042	Mid Devon	South West	1	Mainly Rural	0.389	98.710	6.207	2.694	95.421	0.656	32.924
E07000043	North Devon	South West	2	Largely Rural	0.414	99.590	15.056	3.004	98.545	1.700	34.416
E07000044	South Hams	South West	1	Mainly Rural	0.669	100.000	44.129	6.288	100.000	5.131	37.140
E07000045	Teignbridge	South West	2	Largely Rural	0.583	89.600	10.745	5.174	63.081	1.192	23.149
E07000046	Torridge	South West	1	Mainly Rural	0.349	85.400	12.180	2.171	48.172	1.361	17.235
E07000047	West Devon	South West	1	Mainly Rural	0.430	98.210	13.075	3.209	93.646	1.467	32.774
E07000063	Lewes	South East	3	Urban with Significant Rural	0.619	96.110	6.636	5.646	86.191	0.707	30.848
E07000064	Rother	South East	2	Largely Rural	0.602	100.000	7.775	5.416	100.000	0.841	35.419
E07000065	Wealden	South East	1	Mainly Rural	0.581	89.630	3.988	5.158	63.188	0.395	22.914
E07000067	Braintree	East of England	2	Largely Rural	0.343	96.910	5.428	2.098	89.031	0.564	30.564
E07000068	Brentwood	East of England	3	Urban with Significant Rural	0.586	95.370	15.277	5.212	83.564	1.727	30.168
E07000071	Colchester	East of England	3	Urban with Significant Rural	0.389	100.000	51.973	2.689	100.000	6.056	36.248
E07000072	Epping Forest	East of England	3	Urban with Significant Rural	0.674	99.410	8.663	6.343	97.906	0.946	35.065
E07000074	Maldon	East of England	1	Mainly Rural	0.436	97.630	4.969	3.290	91.587	0.510	31.796
E07000076	Tendring	East of England	2	Largely Rural	0.260	97.010	6.963	1.026	89.386	0.746	30.386
E07000077	Uttlesford	East of England	1	Mainly Rural	0.694	99.800	6.123	6.606	99.290	0.646	35.514
E07000079	Cotswold	South West	1	Mainly Rural	0.646	99.790	19.975	5.983	99.255	2.281	35.840
E07000080	Forest of Dean	South West	1	Mainly Rural	0.743	92.930	1.791	7.234	74.902	0.135	27.424
E07000082	Stroud	South West	3	Urban with Significant Rural	0.745	100.000	4.458	7.253	100.000	0.450	35.901
E07000083	Tewkesbury	South West	2	Largely Rural	0.592	97.030	3.126	5.300	89.457	0.293	31.683
E07000084	Basingstoke and Deane	South East	3	Urban with Significant Rural	0.573	100.000	19.813	5.045	100.000	2.262	35.769
E07000085	East Hampshire	South East	1	Mainly Rural	0.731	98.430	13.162	7.073	94.427	1.477	34.326

E07000089	Hart	South East	3	Urban with Significant Rural	0.616	88.380	7.264	5.601	58.750	0.781	21.711
E07000091	New Forest	South East	3	Urban with Significant Rural	0.561	97.910	16.304	4.901	92.581	1.848	33.110
E07000093	Test Valley	South East	3	Urban with Significant Rural	0.639	94.570	14.092	5.902	80.724	1.587	29.404
E07000094	Winchester	South East	2	Largely Rural	0.972	95.980	37.769	10.171	85.729	4.380	33.427
E07000096	Dacorum	East of England	3	Urban with Significant Rural	0.692	100.000	11.450	6.582	100.000	1.275	35.952
E07000099	North Hertfordshire	East of England	3	Urban with Significant Rural	0.721	98.780	20.987	6.954	95.669	2.400	35.008
E07000105	Ashford	South East	3	Urban with Significant Rural	0.480	100.000	16.524	3.855	100.000	1.874	35.243
E07000108	Dover	South East	3	Urban with Significant Rural	0.368	100.000	15.011	2.416	100.000	1.695	34.704
E07000110	Maidstone	South East	3	Urban with Significant Rural	0.461	100.000	15.098	3.611	100.000	1.705	35.105
E07000111	Sevenoaks	South East	2	Largely Rural	0.705	97.110	13.601	6.746	89.741	1.529	32.672
E07000112	Folkestone and Hythe	South East	3	Urban with Significant Rural	0.337	100.000	18.214	2.016	100.000	2.073	34.696
E07000113	Swale	South East	2	Largely Rural	0.294	100.000	12.714	1.467	100.000	1.424	34.297
E07000115	Tonbridge and Malling	South East	3	Urban with Significant Rural	0.569	99.280	16.346	4.994	97.444	1.853	34.764
E07000116	Tunbridge Wells	South East	3	Urban with Significant Rural	0.629	100.000	29.292	5.768	100.000	3.380	36.383
E07000118	Chorley	North West	3	Urban with Significant Rural	0.499	100.000	4.484	4.106	100.000	0.453	34.853
E07000121	Lancaster	North West	3	Urban with Significant Rural	0.439	99.090	7.352	3.332	96.770	0.791	33.631
E07000124	Ribble Valley	North West	1	Mainly Rural	0.565	99.590	9.383	4.953	98.545	1.031	34.843
E07000127	West Lancashire	North West	3	Urban with Significant Rural	0.481	98.770	8.096	3.867	95.634	0.879	33.460
E07000128	Wyre	North West	2	Largely Rural	0.382	98.540	8.199	2.603	94.817	0.891	32.771

E07000131	Harborough	East Midlands	1	Mainly Rural	1.762	100.000	8.834	20.320	100.000	0.966	40.429
E07000132	Hinckley and Bosworth	East Midlands	2	Largely Rural	0.369	100.000	5.666	2.430	100.000	0.592	34.341
E07000133	Melton	East Midlands	1	Mainly Rural	0.333	91.990	5.915	1.965	71.565	0.622	24.718
E07000134	North West Leicestershire	East Midlands	2	Largely Rural	0.414	97.850	9.179	3.009	92.368	1.007	32.128
E07000136	Boston	East Midlands	3	Urban with Significant Rural	0.242	96.710	6.804	0.800	88.321	0.727	29.949
E07000137	East Lindsey	East Midlands	1	Mainly Rural	0.290	98.890	10.075	1.420	96.060	1.113	32.864
E07000139	North Kesteven	East Midlands	1	Mainly Rural	0.410	99.720	3.394	2.959	99.006	0.324	34.097
E07000140	South Holland	East Midlands	2	Largely Rural	0.301	98.830	1.972	1.557	95.847	0.157	32.520
E07000141	South Kesteven	East Midlands	2	Largely Rural	0.360	98.980	6.458	2.317	96.379	0.686	33.127
E07000142	West Lindsey	East Midlands	1	Mainly Rural	0.370	94.460	4.834	2.440	80.334	0.494	27.756
E07000143	Breckland	East of England	1	Mainly Rural	0.340	99.640	4.545	2.055	98.722	0.460	33.746
E07000144	Broadland	East of England	3	Urban with Significant Rural	0.403	100.000	0.644	2.868	100.000	0.000	34.289
E07000145	Great Yarmouth	East of England	3	Urban with Significant Rural	0.189	96.520	21.573	0.127	87.646	2.469	30.081
E07000146	King's Lynn and West Norfolk	East of England	2	Largely Rural	0.313	97.640	26.368	1.716	91.622	3.035	32.124
E07000147	North Norfolk	East of England	1	Mainly Rural	0.448	100.000	10.964	3.444	100.000	1.218	34.887
E07000149	South Norfolk	East of England	1	Mainly Rural	0.483	89.050	4.355	3.897	61.129	0.438	21.821
E07000151	Daventry	East Midlands	1	Mainly Rural	0.538	91.540	6.499	4.602	69.968	0.691	25.087
E07000152	East Northamptonshire	East Midlands	2	Largely Rural	0.406	93.970	0.727	2.907	78.594	0.010	27.170
E07000155	South Northamptonshire	East Midlands	1	Mainly Rural	1.028	96.020	0.823	10.897	85.871	0.021	32.263
E07000156	Wellingborough	East Midlands	3	Urban with Significant Rural	0.340	92.930	5.607	2.062	74.902	0.586	25.850
E07000163	Craven	Yorkshire and The Humber	1	Mainly Rural	0.485	100.000	11.110	3.926	100.000	1.235	35.054
E07000164	Hambleton	Yorkshire and The Humber	1	Mainly Rural	0.384	90.580	5.591	2.627	66.560	0.584	23.257

E07000165	Harrogate	Yorkshire and The Humber	3	Urban with Significant Rural	0.656	99.750	12.529	6.110	99.113	1.402	35.542
E07000166	Richmondshire	Yorkshire and The Humber	1	Mainly Rural	0.343	98.380	6.179	2.101	94.249	0.653	32.334
E07000167	Ryedale	Yorkshire and The Humber	1	Mainly Rural	0.413	99.200	6.777	2.994	97.160	0.724	33.626
E07000168	Scarborough	Yorkshire and The Humber	3	Urban with Significant Rural	0.261	99.580	38.147	1.042	98.509	4.425	34.659
E07000169	Selby	Yorkshire and The Humber	1	Mainly Rural	0.390	100.000	2.574	2.698	100.000	0.228	34.309
E07000171	Bassetlaw	East Midlands	2	Largely Rural	0.302	99.510	6.011	1.574	98.261	0.633	33.489
E07000175	Newark and Sherwood	East Midlands	2	Largely Rural	0.391	71.860	6.441	2.714	0.106	0.684	1.168
E07000176	Rushcliffe	East Midlands	2	Largely Rural	0.720	92.900	3.294	6.938	74.796	0.313	27.349
E07000177	Cherwell	South East	3	Urban with Significant Rural	1.277	96.930	7.442	14.086	89.102	0.802	34.663
E07000179	South Oxfordshire	South East	1	Mainly Rural	0.861	99.350	3.902	8.747	97.693	0.384	35.608
E07000180	Vale of White Horse	South East	2	Largely Rural	0.801	98.260	4.807	7.975	93.823	0.491	34.097
E07000181	West Oxfordshire	South East	1	Mainly Rural	0.609	100.000	3.883	5.519	100.000	0.382	35.300
E07000187	Mendip	South West	1	Mainly Rural	0.601	99.290	16.614	5.412	97.480	1.884	34.925
E07000188	Sedgemoor	South West	2	Largely Rural	0.372	100.000	5.768	2.465	100.000	0.605	34.357
E07000189	South Somerset	South West	2	Largely Rural	0.436	97.740	6.568	3.293	91.977	0.699	31.990
E07000192	Cannock Chase	West Midlands	3	Urban with Significant Rural	0.505	98.230	6.563	4.174	93.717	0.698	32.863
E07000193	East Staffordshire	West Midlands	3	Urban with Significant Rural	0.386	97.930	7.575	2.655	92.652	0.818	32.042
E07000194	Lichfield	West Midlands	3	Urban with Significant Rural	0.522	100.000	9.845	4.397	100.000	1.086	35.161
E07000196	South Staffordshire	West Midlands	3	Urban with Significant Rural	0.371	98.190	2.785	2.457	93.575	0.253	32.095
E07000197	Stafford	West Midlands	3	Urban with Significant Rural	0.410	98.560	12.005	2.957	94.888	1.340	33.062

E07000198	Staffordshire Moorlands	West Midlands	2	Largely Rural	0.309	92.480	5.029	1.667	73.305	0.517	25.163
E07000200	Babergh	East of England	1	Mainly Rural	0.443	98.920	4.497	3.382	96.166	0.455	33.334
E07000203	Mid Suffolk	East of England	1	Mainly Rural	0.530	71.830	3.443	4.495	0.000	0.330	1.608
E07000210	Mole Valley	South East	3	Urban with Significant Rural	1.813	99.660	17.134	20.969	98.793	1.946	40.569
E07000215	Tandridge	South East	3	Urban with Significant Rural	0.657	96.070	1.999	6.125	86.049	0.160	30.778
E07000216	Waverley	South East	2	Largely Rural	0.885	93.860	15.993	9.053	78.204	1.811	29.689
E07000218	North Warwickshire	West Midlands	1	Mainly Rural	0.380	94.420	1.925	2.575	80.192	0.151	27.639
E07000221	Stratford-on-Avon	West Midlands	1	Mainly Rural	0.744	91.090	14.343	7.252	68.371	1.616	25.746
E07000225	Chichester	South East	2	Largely Rural	0.697	93.550	21.093	6.643	77.103	2.413	28.720
E07000227	Horsham	South East	2	Largely Rural	0.664	98.590	20.237	6.218	94.995	2.312	34.508
E07000235	Malvern Hills	West Midlands	2	Largely Rural	0.518	95.860	3.638	4.341	85.304	0.353	29.999
E07000238	Wychavon	West Midlands	1	Mainly Rural	1.218	99.900	13.053	13.328	99.645	1.464	38.146
E07000239	Wyre Forest	West Midlands	3	Urban with Significant Rural	0.290	99.320	15.553	1.414	97.586	1.759	33.586
E07000242	East Hertfordshire	East of England	3	Urban with Significant Rural	0.648	96.420	24.976	6.014	87.291	2.871	32.059
E07000244	East Suffolk	East of England	2	Largely Rural	0.423	89.020	10.624	3.125	61.022	1.178	21.775
E07000245	West Suffolk	East of England	2	Largely Rural	0.428	100.000	25.984	3.189	100.000	2.990	35.393
E07000246	Somerset West and Taunton	South West	2	Largely Rural	0.407	98.320	11.112	2.913	94.036	1.235	32.728

CARTI Index Scores

LAD20NM	Region	RUCCD	RUCNM	Need Score	Capacity Score	Rural CAEV Potential Score
Isles of Scilly	South West	1	Mainly Rural	48.444	91.516	69.980
Rutland	East Midlands	1	Mainly Rural	88.752	38.279	63.515
South Hams	South West	1	Mainly Rural	77.976	37.140	57.558
Cotswold	South West	1	Mainly Rural	78.141	35.840	56.990
Derbyshire Dales	East Midlands	1	Mainly Rural	76.789	35.053	55.921
South Northamptonshire	East Midlands	1	Mainly Rural	78.587	32.263	55.425
West Devon	South West	1	Mainly Rural	76.385	32.774	54.579
Ryedale	Yorkshire and The Humber	1	Mainly Rural	75.394	33.626	54.510
Huntingdonshire	East of England	1	Mainly Rural	69.623	35.430	52.527
Breckland	East of England	1	Mainly Rural	70.626	33.746	52.186
South Holland	East Midlands	2	Largely Rural	70.047	32.520	51.284
East Lindsey	East Midlands	1	Mainly Rural	68.308	32.864	50.586
Harborough	East Midlands	1	Mainly Rural	60.249	40.429	50.339
North Devon	South West	2	Largely Rural	65.255	34.416	49.836
Cornwall	South West	1	Mainly Rural	62.980	36.330	49.655
North Norfolk	East of England	1	Mainly Rural	63.700	34.887	49.294
North Kesteven	East Midlands	1	Mainly Rural	62.727	34.097	48.412
Eden	North West	1	Mainly Rural	63.006	33.252	48.129
South Kesteven	East Midlands	2	Largely Rural	63.129	33.127	48.128
Babergh	East of England	1	Mainly Rural	62.497	33.334	47.916
Mid Devon	South West	1	Mainly Rural	62.859	32.924	47.891
Mendip	South West	1	Mainly Rural	60.197	34.925	47.561
Daventry	East Midlands	1	Mainly Rural	69.677	25.087	47.382
Somerset West and Taunton	South West	2	Largely Rural	61.512	32.728	47.120

King's Lynn and West Norfolk	East of England	2	Largely Rural	62.105	32.124	47.115
East Cambridgeshire	East of England	1	Mainly Rural	58.520	35.063	46.791
South Derbyshire	East Midlands	3	Urban with Significant Rural	59.284	34.213	46.748
Dorset	South West	2	Largely Rural	60.742	32.527	46.634
North Lincolnshire	Yorkshire and The Humber	3	Urban with Significant Rural	61.361	31.896	46.628
South Somerset	South West	2	Largely Rural	60.806	31.990	46.398
Wiltshire	South West	2	Largely Rural	55.965	36.774	46.370
Bassetlaw	East Midlands	2	Largely Rural	59.021	33.489	46.255
Hambleton	Yorkshire and The Humber	1	Mainly Rural	69.155	23.257	46.206
East Northamptonshire	East Midlands	2	Largely Rural	64.396	27.170	45.783
Melton	East Midlands	1	Mainly Rural	66.701	24.718	45.709
Craven	Yorkshire and The Humber	1	Mainly Rural	55.983	35.054	45.518
North West Leicestershire	East Midlands	2	Largely Rural	58.537	32.128	45.332
Teignbridge	South West	2	Largely Rural	67.481	23.149	45.315
West Suffolk	East of England	2	Largely Rural	54.502	35.393	44.947
West Lindsey	East Midlands	1	Mainly Rural	62.087	27.756	44.922
Northumberland	North East	2	Largely Rural	51.663	37.433	44.548
Sedgemoor	South West	2	Largely Rural	54.731	34.357	44.544
Uttlesford	East of England	1	Mainly Rural	53.192	35.514	44.353
Torridge	South West	1	Mainly Rural	71.352	17.235	44.294
South Cambridgeshire	East of England	2	Largely Rural	57.989	29.634	43.811
Fenland	East of England	2	Largely Rural	54.347	33.155	43.751
Tewkesbury	South West	2	Largely Rural	55.130	31.683	43.406
East Hertfordshire	East of England	3	Urban with Significant Rural	52.714	32.059	42.386
County Durham	North East	2	Largely Rural	46.667	37.494	42.080
Harrogate	Yorkshire and The Humber	3	Urban with Significant Rural	48.120	35.542	41.831

Boston	East Midlands	3	Urban with Significant Rural	53.688	29.949	41.818
South Norfolk	East of England	1	Mainly Rural	61.081	21.821	41.451
Broadland	East of England	3	Urban with Significant Rural	48.444	34.289	41.367
Stroud	South West	3	Urban with Significant Rural	46.269	35.901	41.085
Selby	Yorkshire and The Humber	1	Mainly Rural	47.680	34.309	40.994
Lichfield	West Midlands	3	Urban with Significant Rural	46.174	35.161	40.668
Brentwood	East of England	3	Urban with Significant Rural	51.064	30.168	40.616
Braintree	East of England	2	Largely Rural	50.577	30.564	40.571
East Riding of Yorkshire	Yorkshire and The Humber	2	Largely Rural	46.394	34.437	40.416
North Hertfordshire	East of England	3	Urban with Significant Rural	45.642	35.008	40.325
Richmondshire	Yorkshire and The Humber	1	Mainly Rural	48.248	32.334	40.291
Epping Forest	East of England	3	Urban with Significant Rural	44.888	35.065	39.977
Rushcliffe	East Midlands	2	Largely Rural	51.817	27.349	39.583
North Somerset	South West	3	Urban with Significant Rural	45.534	33.456	39.495
Colchester	East of England	3	Urban with Significant Rural	42.704	36.248	39.476
Central Bedfordshire	East of England	2	Largely Rural	46.499	32.380	39.439
Hinckley and Bosworth	East Midlands	2	Largely Rural	44.439	34.341	39.390
Vale of White Horse	South East	2	Largely Rural	43.686	34.097	38.891
Redcar and Cleveland	North East	3	Urban with Significant Rural	39.841	37.685	38.763
East Devon	South West	2	Largely Rural	57.995	19.509	38.752
Bath and North East Somerset	South West	3	Urban with Significant Rural	41.960	35.347	38.654
Forest of Dean	South West	1	Mainly Rural	49.853	27.424	38.639
Cherwell	South East	3	Urban with Significant Rural	42.456	34.663	38.560
High Peak	East Midlands	2	Largely Rural	42.140	34.611	38.375
Herefordshire, County of	West Midlands	2	Largely Rural	43.639	32.933	38.286
Rother	South East	2	Largely Rural	40.947	35.419	38.183
Wellingborough	East Midlands	3	Urban with Significant Rural	50.186	25.850	38.018

Maldon	East of England	1	Mainly Rural	43.278	31.796	37.537
East Hampshire	South East	1	Mainly Rural	40.577	34.326	37.451
West Berkshire	South East	3	Urban with Significant Rural	38.292	36.559	37.426
Dacorum	East of England	3	Urban with Significant Rural	38.054	35.952	37.003
Newark and Sherwood	East Midlands	2	Largely Rural	70.928	1.168	36.048
Mid Suffolk	East of England	1	Mainly Rural	70.446	1.608	36.027
Scarborough	Yorkshire and The Humber	3	Urban with Significant Rural	37.327	34.659	35.993
East Suffolk	East of England	2	Largely Rural	50.077	21.775	35.926
Basingstoke and Deane	South East	3	Urban with Significant Rural	35.890	35.769	35.829
Tendring	East of England	2	Largely Rural	40.919	30.386	35.652
Wychavon	West Midlands	1	Mainly Rural	33.142	38.146	35.644
West Oxfordshire	South East	1	Mainly Rural	35.813	35.300	35.556
Winchester	South East	2	Largely Rural	37.673	33.427	35.550
Test Valley	South East	3	Urban with Significant Rural	41.014	29.404	35.209
Chichester	South East	2	Largely Rural	40.800	28.720	34.760
Mole Valley	South East	3	Urban with Significant Rural	28.721	40.569	34.645
New Forest	South East	3	Urban with Significant Rural	36.148	33.110	34.629
Shropshire	West Midlands	2	Largely Rural	34.866	33.856	34.361
Great Yarmouth	East of England	3	Urban with Significant Rural	38.390	30.081	34.235
Stafford	West Midlands	3	Urban with Significant Rural	35.387	33.062	34.224
Malvern Hills	West Midlands	2	Largely Rural	37.400	29.999	33.700
South Oxfordshire	South East	1	Mainly Rural	31.753	35.608	33.680
Stratford-on-Avon	West Midlands	1	Mainly Rural	41.199	25.746	33.472
North Warwickshire	West Midlands	1	Mainly Rural	38.785	27.639	33.212
Horsham	South East	2	Largely Rural	31.736	34.508	33.122
South Lakeland	North West	1	Mainly Rural	39.745	25.217	32.481
East Staffordshire	West Midlands	3	Urban with Significant Rural	32.879	32.042	32.460
Buckinghamshire	South East	3	Urban with Significant Rural	27.809	35.644	31.727

Swale	South East	2	Largely Rural	29.033	34.297	31.665
Tunbridge Wells	South East	3	Urban with Significant Rural	26.845	36.383	31.614
South Staffordshire	West Midlands	3	Urban with Significant Rural	30.728	32.095	31.411
Waverley	South East	2	Largely Rural	32.712	29.689	31.201
Staffordshire Moorlands	West Midlands	2	Largely Rural	36.742	25.163	30.952
Maidstone	South East	3	Urban with Significant Rural	26.285	35.105	30.695
Ashford	South East	3	Urban with Significant Rural	25.607	35.243	30.425
Allerdale	North West	1	Mainly Rural	35.768	24.986	30.377
Wealden	South East	1	Mainly Rural	37.693	22.914	30.303
Isle of Wight	South East	1	Mainly Rural	20.849	39.683	30.266
Bedford	East of England	3	Urban with Significant Rural	44.619	15.625	30.122
Sevenoaks	South East	2	Largely Rural	27.320	32.672	29.996
Copeland	North West	1	Mainly Rural	40.894	18.959	29.927
Dover	South East	3	Urban with Significant Rural	25.108	34.704	29.906
Bolsover	East Midlands	3	Urban with Significant Rural	41.756	18.035	29.896
Tonbridge and Malling	South East	3	Urban with Significant Rural	24.953	34.764	29.858
Wyre Forest	West Midlands	3	Urban with Significant Rural	25.332	33.586	29.459
Tandridge	South East	3	Urban with Significant Rural	27.632	30.778	29.205
Folkestone and Hythe	South East	3	Urban with Significant Rural	23.410	34.696	29.053
Ribble Valley	North West	1	Mainly Rural	22.860	34.843	28.851
Lewes	South East	3	Urban with Significant Rural	26.042	30.848	28.445
Carlisle	North West	3	Urban with Significant Rural	22.989	32.167	27.578
Wyre	North West	2	Largely Rural	19.482	32.771	26.126
Cannock Chase	West Midlands	3	Urban with Significant Rural	18.524	32.863	25.694
Cheshire East	North West	3	Urban with Significant Rural	16.113	35.248	25.680
Cheshire West and Chester	North West	3	Urban with Significant Rural	17.477	31.594	24.535
Lancaster	North West	3	Urban with Significant Rural	13.619	33.631	23.625
Hart	South East	3	Urban with Significant Rural	24.893	21.711	23.302
West Lancashire	North West	3	Urban with Significant Rural	12.844	33.460	23.152

Chorley	North West	3	Urban with Significant Rural	6.422	34.853	20.638
Barrow-in-Furness	North West	3	Urban with Significant Rural	5.651	32.270	18.961

APPENDIX D – CASE STUDIES

Participant Information Sheet

Project title CAEV Rural Transport Index Validation

Researcher Joseph George Walters

Supervisors Stuart Marsh; Lucelia Rodrigues

Before you decide to take part in this study it is important that you understand why this research is being undertaken and what it involves. Please read the following information carefully. You may discuss it with others and your employer. After reading the information below please take the time to decide whether you wish to take part or not.

Project Information

This PhD project is investigating the potential for rural road Connected, Autonomous and Electric Vehicle (CAEV) implementation in three stages. Stage 1 investigated digital and physical infrastructure requirements which included conducting road tests to assess satellite positioning, road "readability", and connectivity reliability. Stage 2 investigated the extent of transport planner awareness and understanding of CAEVs and infrastructure to assess the state and readiness of the industry for CAEV implementation. Finally, based on the findings from Stages 1 and 2, Stage 3 has resulted in the development of a measurement index intended to assess the needs and capacity of rural areas to support the implementation of CAEVs.

The CAEV Rural Transport Index (CARTi) is the result of this PhD project and takes a small selection of transport-based measurement indicators to assess rural area need and capacity to support CAEV implementation. The aim is for the CARTi to provide a simple yet useful tool for transport planners to assess potential for CAEV implementation, with detailed levels of the index informing planners of rural needs that can be supported by

CAEV implementation as well as gaps in capacity which may need to be improved for effective CAEV implementation.

To complete Stage 3 an assessment of the validity and usefulness of the CARTi is being undertaken and we are seeking professionals with knowledge of transport systems within the selected case study areas to contribute their critical perspectives regarding the CARTi, its validity, and its usefulness.

Participant Selection and Participation

You have been selected as a participant due to your knowledge and experience in the transport sector in your region, which has been selected as one of three case studies. We believe that your perspectives on the content described will be valuable to this research.

You may decide whether you would prefer to answer in an online or in-person in a one-to-one or workshop environment for up to 1 hour. Alternatively, your contribution can be in written form and returned to the researcher at joseph.walters@nottingham.ac.uk. Participation in this study is entirely voluntary and you may refuse specific questions or withdraw from the study at your discretion. Please ensure that you read and understand this information sheet and sign the consent form before partaking in this study.

Contact

If you want to know more about taking part in this study, please contact either the researcher or their supervisors at the email addresses below.

Researcher: joseph.walters@nottingham.ac.uk

Supervisors: stuart.marsh@nottingham.ac.uk; lucelia.rodriguez@nottingham.ac.uk

Participant Consent Form

Study title CAEV Rural Transport Index Validation

Researcher Joseph George Walters

Supervisors Stuart Marsh; Lucelia Rodrigues

- I have read the Participant Information Sheet and the nature and purpose of the research project has been explained to me. I understand and agree to take part.
- I have read and understand the Participant Consent Form and Participant Privacy Notice below.
- I understand the purpose of the research project and my involvement in it.
- I understand that I may withdraw from the research project at any stage and that this will not affect my status now or in the future.
- I understand that any in-person discussions about the research will be audio recorded.
- I understand that any responses I provide will be stored electronically in line with the University of Nottingham data protection guidelines. This data will be password protected and only accessible by the researcher. The researcher may share this data with their supervisors only.
- I understand that I may contact the researcher or supervisors if I require further information about the research.
- To improve the validity of the study, the researcher would like to request permission to record and use your job title, role and employer information. This information will be published. Please select one of the following:
    - I give permission for the researcher to publish my job title, role and employer information only. I understand that I will not be directly identified by name.
    - I wish to remain completely anonymous. The researcher may not relate any personal details to my responses to this research. I understand I am still able to participate in the study.

Signed ………………………………………………………………………… (research participant)

Print name ……………………………………………………………………… **Date** …………………………………

Participant Privacy Notice

Privacy information for Research Participants

For information about the University's obligations with respect to your data, who you can get in touch with and your rights as a data subject, please visit: https://www.nottingham.ac.uk/utilities/privacy.aspx.

Why we collect your personal data

We collect personal data under the terms of the University's Royal Charter in our capacity as a teaching and research body to advance education and learning. Specific purposes for data collection on this occasion are to identify your employer and the geographic region in which you work. Audio data will be recorded for transcription purposes.

Legal basis for processing your personal data under GDPR

The legal basis for processing your personal data on this occasion is Article 6(1a) consent of the data subject.

How long we keep your data

The University may store your data for up to 25 years and for a period of no less than 7 years after the research project finishes. The researchers who gathered or processed the data may also store the data indefinitely and reuse it in future research.

Who will use your data?

Measures to safeguard your stored data include the use of password protected UoN OneDrive folders which will only be accessible by the researcher until the end of the research project and shared only with their supervisors.

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator from a University of Nottingham email address or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name Joseph Walters

Reviewed by: M08

Date: 15/11/2021

- [x] Approval awarded - no changes required
- [ ] Approval awarded - subject to required changes (see comments below)
- [ ] Approval pending - further information & resubmission required (see comments)
- [ ] Approval declined – reasons given below

Comments:

Please note:

5. The approval only covers the participants and trials specified on the form and further approval must be requested for any repetition or extension to the investigation.
6. The approval covers the ethical requirements for the techniques and procedures described in the protocol but does not replace a safety or risk assessment.
7. Approval is not intended to convey any judgement on the quality of the research, experimental design or techniques.
8. Normally, all queries raised by reviewers should be addressed. In the case of conflicting or incomplete views, the ethics committee chair will review the comments and relay these to the applicant via email. All email correspondence related to the application must be copied to the Faculty research ethics administrator.

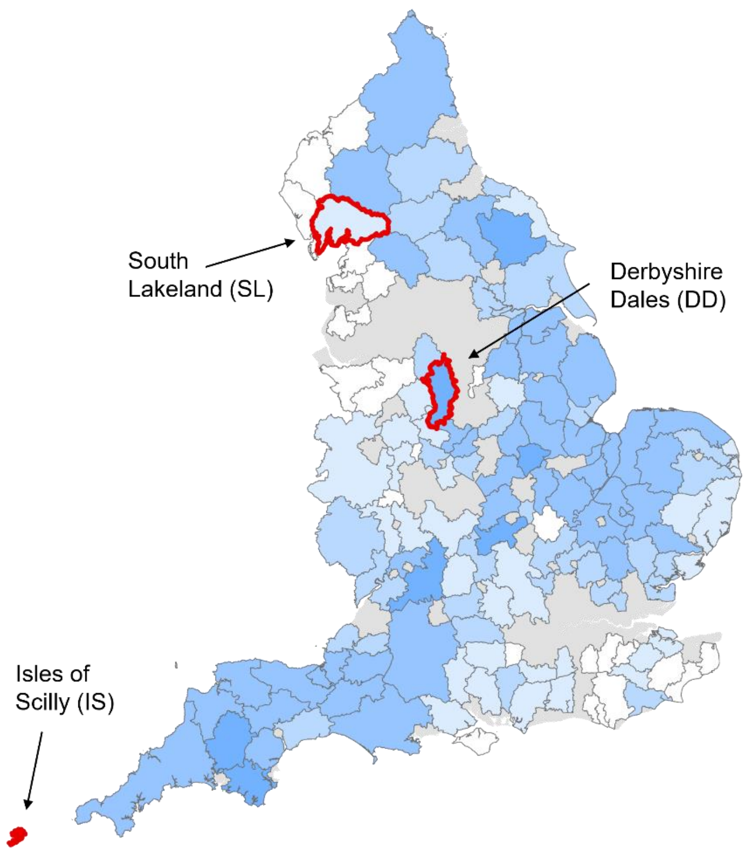
Any problems which arise during the course of the investigation must be reported to the Faculty Research Ethics Committee

Project Abstract and Case Study Data

This PhD project is investigating the potential for rural road Connected, Autonomous and Electric Vehicle (CAEV) implementation in three stages. Stage 1 investigated digital and physical infrastructure requirements which included conducting road tests to assess satellite positioning, road "readability", and connectivity reliability. Stage 2 investigated the extent of transport planner awareness and understanding of CAEVs and infrastructure to assess the state and readiness of the industry for CAEV implementation. Finally, based on the findings from Stages 1 and 2, Stage 3 has resulted in the development of a measurement index intended to assess the needs and capacity of rural areas to support the implementation of CAEVs.

The CAEV Rural Transport Index (CARTi) is the result of this PhD project and takes a small selection of transport-based measurement indicators to assess rural area need and capacity to support CAEV implementation. The aim is for the CARTi to provide a simple yet useful tool for transport planners to assess potential for CAEV implementation, with detailed levels of the index informing planners of rural needs that can be supported by CAEV implementation as well as gaps in capacity which may need to be improved for effective CAEV implementation.

To complete Stage 3 an assessment of the validity and usefulness of the CARTi is being undertaken and we are seeking professionals with knowledge of transport systems within the selected case study areas to contribute their critical perspectives regarding the CARTi, its validity, and its usefulness.

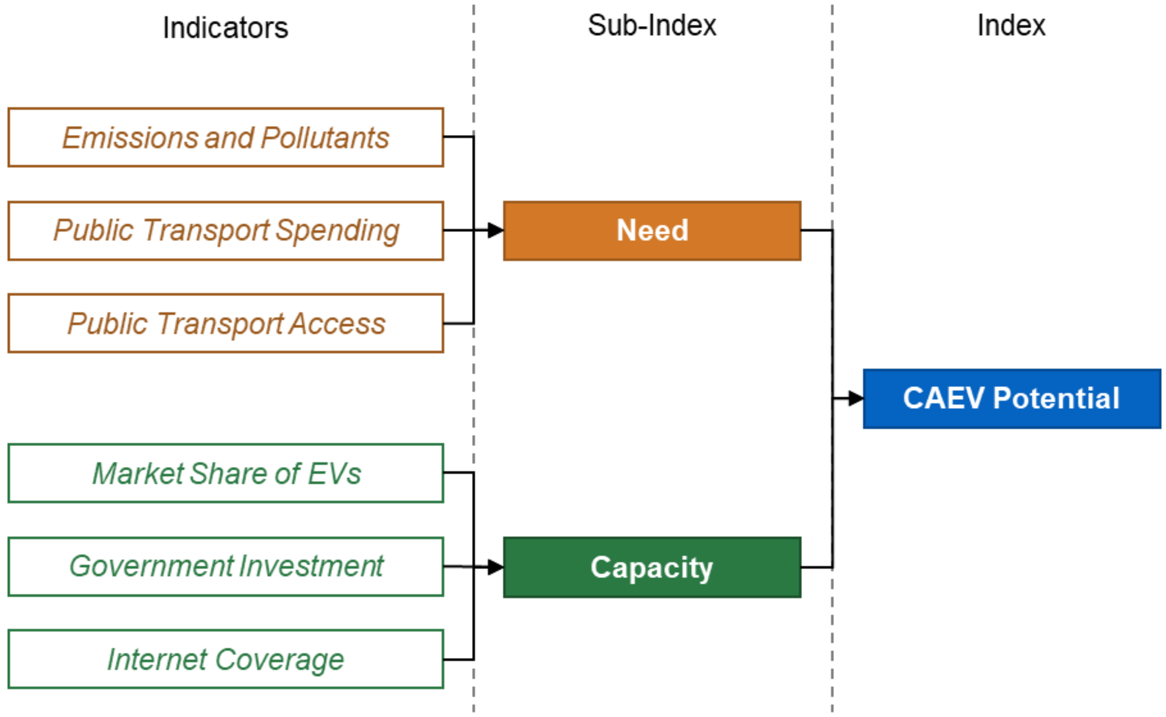


English rural Local Authorities mapped by their CARTi scores with selected case studies highlighted:

DD – Derbyshire Dales
SL – South Lakeland
IS – Isles of Scilly

The CARTi consists of six transport measurement indicators that combine to create two sub-indexes. One sub-index identifies a rural local authority's potential *need* for CAEV implementation, and the other a rural local authority's potential *capacity* to support such CAEV implementation. An overall CARTi score highlights areas with the most potential for CAEV implementation.

The scores (from 0 to 100) reflect the extent of need, capacity and proposed CAEV implementation potential. For example, a high need score reflects high levels of need.



Scoring levels within the CARTi and indicator relationships

Indicator/Index	Score (0 – 100 based on comparison with other English rural Local Authorities)			Data and Method used (per Local Authority) on which the score is based
	DD	SL	IS	
Emissions and Pollutants	79.0	55.0	0.0	Annual tonne of CO_2 per capita from transport on A and B roads
Personal Transport Spending	87.1	0.0	100.0	Percentage of total weekly expenditure on personal transport in GBP per week
Public Transport Access	64.3	64.2	45.3*	Percentage of population outside of acceptable walking distance to the nearest bus stop – based on LSOA population centroids, bus stop GTFS data and GIS network analysis
Needs-based Sub-index	**76.8**	**39.7**	**48.4**	**Average score of Emissions and Pollutants, Personal Transport Spending and Public Transport Access**
Market Share of EVs	4.8	4.2	100.0	Percentage of total cars licensed as Battery Electric Vehicles (BEVs)
Government Investment	1.9	3.4	100.0	Total investment in transport and transport infrastructure in GBP per capita
Internet Coverage	98.4	68.1	74.5	Percentage of A and B roads with reliable 4G coverage
Capacity-based Sub-index	**35.1**	**25.2**	**91.5**	**Average Score of Market Share of EVs, Government Investment and Internet Coverage**
CARTi (CAEV Rural Transport Index)	**55.9**	**32.5**	**70.0**	**Average of Need and Capacity Sub-indexes**

* data unavailable so the average value for rural classification 1 is applied

Workshop Question Schedule

Accuracy

To what extent do each of the six index indicators and scores reflect the current state of your region?

To what extent do you agree with the total need and capacity scores for your region?

To what extent do you agree with the overall CARTi score for your region?

Validity

Which indicators stand out as being particularly relevant or irrelevant to rural CAEV implementation?

Are there any indicators missing that you believe are crucial to measuring a rural areas CAEV implementation need, capacity or potential?

How valid are the data and methods for the indicators? Can you suggest any alternatives?

Usefulness

To what extent are the needs-based indicators useful in identifying aspects that could be improved by CAEV implementation in your region?

To what extent are the capacity-based indicators useful in identifying aspects that can support CAEV implementation in your region?

To what extent would transport planning professionals find this index useful and use it to take steps towards CAEV implementation? Give reasons for your answer.

Rail Integration

How do you believe CAEVs could be most effectively integrated with rail infrastructure and services in your region?

In what ways, if any, can rail infrastructure support the rural implementation of CAEVs?

To what extent could the CARTi be used in planning and developing rail infrastructure and services in your region?

General

Do you have any other thoughts, comments, or suggestions regarding the CARTi and this research?