future transportation

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A Rural Transport Implementation Index for Connected, Autonomous and Electric Vehicles

Joseph George Walters [1,*], Stuart Marsh [1] and Lucelia Rodrigues [2]

[1] Nottingham Geospatial Institute, University of Nottingham, Triumph Road, Nottingham NG7 2TU, UK
[2] Department of Architecture and Built Environment, University of Nottingham, University Park, Nottingham NG7 2RD, UK
* Correspondence: joseph.walters@nottingham.ac.uk or joegewa@gmail.com

Abstract: With connected, autonomous and electric vehicles (CAEV) developing rapidly, there is a need to better support their implementation into rural scenarios, where there are numerous transport challenges. The potential safety, efficiency and sustainability benefits of CAEVs could provide significant value for rural communities if implemented correctly. However, transport planner knowledge of CAEVs and their digital and physical infrastructure requirements in the UK is limited and, despite interest, there is little time or resources available to effectively explore rural CAEV implementation potential. This paper therefore describes the methodology behind, and development of, the CAEV Rural Transport Index (CARTI), based on existing literature and a combination of existing and developed indicators. The CARTI's purpose is to identify the levels of need, capacity and overall potential of different rural areas to support rural CAEV implementation. Application of the CARTI to several case study areas reveals a range of benefits, reviewed through workshops with local transport professionals. Ultimately, the CARTI is identified as a much-needed tool to support the implementation of CAEVs in rural areas, with potential for further development to establish it as a successful and long-term planning tool.

Keywords: connected vehicles; autonomous vehicles; electric vehicles; index development; development indicators; transport planning; rural transport systems; planning; mobility; electrification

Citation: Walters, J.G.; Marsh, S.; Rodrigues, L. A Rural Transport Implementation Index for Connected, Autonomous and Electric Vehicles. *Future Transp.* **2022**, *2*, 753–773. https://doi.org/10.3390/futuretransp2030042

Academic Editor: Grzegorz Karoń

Received: 30 May 2022
Accepted: 13 September 2022
Published: 16 September 2022

1. Introduction

In an increasingly congested world, large and expensive transport infrastructure projects are increasingly less viable as solutions to transport challenges [1,2]. Connected, autonomous and electric vehicles (CAEV) offer an effective and less disruptive alternative that can be achieved through the integration of existing and developing transport, communication, control and information processing technologies [3].

CAEVs refer to autonomous, or "driverless", vehicles with high levels of connected functionality powered by electric powertrains. As defined by [4,5], CAEVs feature five distinct components:

- 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 vehicle-to-everything (V2X) capabilities through wireless communication links;
- An energy storage system including charging and battery technologies.

There are six levels of autonomy as defined by SAE International [6]. Each level details the autonomous functions of a vehicle and defines the level of human interaction, if any, required to operate the vehicle. When discussing CAEVs throughout this paper, the authors are referring to CAEVs with automation levels 3 or 4. 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 consideration of level 5 CAEVs has been made, the authors note that this technology, specifically in rural scenarios, is underdeveloped and unlikely to be achieved in the near future to which this paper refers.

CAEVs are well placed to solve the challenges of increasing mobility demand and harmful emissions, being able to offer transport solutions that are safer, more efficient and more sustainable [7–12]. For example, communication-based systems such as demand-responsive transport (DRT) can improve accessibility by supplementing public transport systems [13–15], and Mobility as a Service (MaaS) can support demand-responsive CAEV solutions though unified travel management platforms and wireless communication infrastructure [16–19]. This makes CAEVs, combined with DRT and MaaS, amongst the most researched automotive technologies and transport solutions [5].

CAEVs will be particularly valuable if accompanied by effective planning and infrastructure management, which could include the provision of transport hubs such as interchanges and park and ride facilities [20–22]. However, there are numerous barriers to the implementation of CAEVs, including the experimental nature and effectiveness of the technology, high technological costs, lack of real-world testing, the challenges of integration with existing road users, user perceptions and trust and regulatory challenges [23–32].

In addition, CAEVs are predominantly an urban-serving technology [21,29], with the most prominent examples being trialled in major cities. This is despite the fact that it is rural communities that are the most isolated, lack accessibility, are at the most risk of severe traffic accidents and lack digital connectivity [30,31]. Therefore, CAEVs have the potential to address rural social and economic needs and help close the gap between rural and urban communities [21]. Rural communities have a significant amount to gain from CAEV development, which means that rural priorities and considerations should be central to future CAEV developments.

Previous research regarding rural CAEV development found that transport planner knowledge of CAEVs and their digital and physical infrastructure requirements in the UK was limited and, despite interest, there were few resources available for transport planners to effectively explore rural CAEV implementation potential [31]. There is also evidence that, without effective policy and planning, CAEV implementation could cause increased congestion and reduce accessibility [33]. Consequently, there is a need for a planning solution that highlights the requirements for CAEV technologies to operate in rural areas and on rural roads in the UK. Such a solution would equip today's transport planning professionals, who are responsible for present and future transportation systems, with the knowledge and understanding of CAEVs required to plan for and develop modern rural transport systems.

Hard infrastructures have typical minimum design lives of fifty years. However, the rapid development of CAEV technology highlights a need to understand future technologies now, so that systems and strategies can be implemented to create future-ready transport environments. A straightforward planning solution to support transport planners in implementing CAEVs and infrastructure in rural areas is needed so that rural communities are able to experience the benefits promised by such technologies.

Therefore, in this paper, the authors reflect on the findings of Walters et al. [31] to develop the CAEV Rural Transport Index (CARTI). This paper also assumes the definition of "rural roads" presented in previous related works [30,31]. 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. Therefore, the CARTI's purpose is to identify the levels of need, capacity and overall potential of different rural areas in England, to support transport planner decision making regarding rural CAEV implementation.

Through the development of the CARTI, which is presented for the first time in this paper, the authors make the following contributions to knowledge:

- Highlight the need to support transport planners in addressing the unique challenges facing the rural implementation of CAEV technologies;
- Propose a unique methodology that links the measurement domains of transportation development, rural development and technological development together into a single future transport measurement index for the first time;
- Present a simple yet novel solution in the form of the CARTI to aid transport planner understanding of rural CAEV requirements and accelerate rural CAEV implementation;
- Form a baseline from which further studies can develop future transport technology indexes to contribute to CAEV solutions across the UK and globally.

2. Transport Planning Indexes

An index is a collection of indicators (measurements, parameters or variables) identified to be significant for a particular sector of development [34]. 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 [35,36]. 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 [34]. Sustainability plays a large part in the development of any index and is therefore a key consideration throughout the CARTI methodology [35–46].

The CARTI aims to equally distribute transportation development opportunities, in the form of CAEV technology, among rural populations. The aim is to bridge the technological transportation development gap between rural and urban populations. As a policy analysis tool, an index that can be applied across regions for comparison and equity purposes is highly desired [47]. This is a particularly important function of an index when considering application across rural regions, which have been shown to be lacking in many development areas, including transportation [13,21,34,48–52]. Indicators are able to capture the multidimensionality of sustainable transport and break down concepts into management units for comparison, benchmarking and communication [39]. Further, the CARTI reveals opportunities for CAEV need and determines the level of capacity of a rural area within which local transport planners could develop appropriate CAEV-based transport systems. This is a useful function that will aid transport planner decision making regarding understanding CAEV requirements [31].

The development domains of interest in this paper are those of transport development and rural development. There is an abundance of existing literature regarding both these development domains, which includes studies on the development of measurement indexes to assess them. The existing literature indicates that rural development index research primarily focuses on societal development using measures relating to health and personal wealth [34,47,48,53–56]. On the other hand, transport development index research often takes a large-scale approach, exploring nationwide transportation development [35,40,42,43,45,46,57–59]. Any smaller-scale analyses focus on the development of urban, or inter-urban, transportation systems, rather than rural systems [36,41,60]. Based on the literature review, it is rare to find explicit research that unifies both transport and rural development domains. Rural development index research rarely considers transport elements, whilst transport development indexes primarily focus on urban systems. This highlights a gap in the research, where this paper and the CARTI contribute to knowledge.

The CARTI therefore measures the need and capacity of transportation systems for specifically rural areas, with a focus on modern transportation technologies. With the rapid development of modern and future transport systems and technologies, it is also rare to find indexes which consider such modern transport technology. However, there are exceptions of note. Whilst not explicitly an index, the Rural Mobility Toolkit addresses solutions to rural challenges, including suggestions on the theme of modern transport, including self-driving and ride-share innovations, active electric and micro-mobility solutions and autonomous vehicles [61]. More prominent in this field is the KPMG Autonomous Vehicle Readiness Index (AVRI), which measures a country's potential readiness for autonomous vehicle implementation with international comparison [59]. As the only AV-specific index found, the AVRI was used as an example of how to collate an effective list of indicators, and also how to obtain AV-specific indicators. Whilst detailed, the AVRI measures readiness on an international rather than local scale, as the CARTI aims to address, and profiles a selection of major cities citing interesting autonomous vehicle developments, although these are not ranked. Many of the AVRI's indicators were not applicable to local rural regions within the countries highlighted. Therefore, the indicators that could be scaled or be adapted to become applicable to local rural levels were assessed as part of the indicator selection process described in Section 3.4 of this paper.

3. Methodology

CAEVs and their associated technologies, if implemented effectively, can be capable of improving rural transport systems and bring accessibility benefits to rural communities. However, the challenges to such implementation are broad but, most notably, rural transport planners are poorly equipped to understand the opportunities and requirements for effective rural CAEV implementation [31]. Therefore, this paper has proposed the CAEV Rural Transport Index (CARTI) as a straightforward planning tool to identify the levels of need, capacity and overall potential of different rural areas to support CAEV implementation. The following methodology describes the CARTI's development based on literature reviews of indexes measuring the domains of rural and transport development, and method-based index development studies.

3.1. Dual-Element 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 [55]. 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 [62,63]. 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) [55], 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.

3.2. CARTI Development Method

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 [39]. 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 [39]. 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 [64]. MCDA methods vary in the way they operationalise the index indicators but most are based on linear weighted sum models [65]. These simple models are almost universally more accurate than the intuitive judgements of decision makers [66]. 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 [39] and MCDA [65] methodologies. The stages and steps of the CARTI methodology are described in Table 1.

Table 1. CARTI development methodology.

Scheme	Step	Description	Outputs
1. Defining index goals	I	Structure decision problem based on research aims and identified development domains	Results inform step II and step III
	II	Define CARTI goals and need/capacity element requirements	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	202 existing indicators, their measurement methods and original sources
	IV	Consolidate indicator collection: remove irrelevant indicators; group similar indicators; review relevant indexes	38 consolidated indicator groups
	V	Determine indicator evaluation criteria including quality and measurement requirements	Quality criteria
	VI	Select initial index indicators	6 indicators (3 for each element)
	VII	Evaluate indicator quality and measurement performance	6 indicators with absolute measurement values

Table 1. *Cont.*

Scheme	Step	Description	Outputs
3. Index construction	VIII	Determine scoring method to convert indicator measurements to comparative scores	Contributes to output X
	IX	Determine indicator weighting procedure	Contributes to output X
	X	Apply scores and weights to rank indicators and determine element and index scores	6 indicators with relative scores between 0 and 100
	XI	Assess the ability of the index to support decision making	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, described in Table 1, stakeholders were engaged post index development. However, professionals were engaged in the investigations of Walters et al. [31], 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 [66], further justifying the decision not to engage stakeholders mid-methodology.

3.3. Defining CARTI Domains and Goals

The definition of research aims was needed to define the direction of the index so that relevant and precise indicators could be selected [39]. This ensured that the indicator selection process reflected the relevant characteristics of the research domains for a comprehensive and complete index [55]. The ultimate aim of this paper is to enhance the potential for CAEVs to contribute to rural transport development through effective implementation. By way of nature, 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 also addressing the additional goal of providing transport planners with a straightforward CAEV decision-making aid.

Further to the research goals, the major research domains of rural development and transport development were considered. Through the development of the CARTI, these domains are brought together and integrate the potential of future transport technologies to support rural development. Whilst these major domains are consolidated into the CARTI, they are distinctly separate in the literature, as previously described. Due to the minimal literature available 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.

Considering the domain of rural development, there were three essential factors, summarised by Kim et al. [55], that were common across the literature. These were as follows: using local people and government as the main development agents; measurements must contribute towards improving quality of life and/or sustainable development; and 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, Jeon et al. [38] found that 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. 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 [46]. 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. Zito et al. [36] identified a set of key factors that influenced sustainable transportation development, which appear to be more sustainably balanced than previous research. 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 [35,36,41–44,46,67]. 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 [30,31]. 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 [68]. As such, sustainable transportation must impact economic, environmental and societal wellbeing domains [38]; 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 [39,40,45,46]. Further, sustainability is central to the ELASTIC methodology [39], 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 [60]. 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 [45]. 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.

Based on the literature review findings, the CARTI's goals are described in Table 2. 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 2, 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 2. 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.

Table 2. CARTI goals and definitions.

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

3.4. Indicator Selection

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 [47,69].

For example, a review of KPMG's AVRI [59] 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.

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.

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 [48]. In addition, the indicators selected need to have been theoretically robust, yet simple enough to be understandable and interactive for planning processes [46]. 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. As a result, Table 3 describes the CARTI indicator quality criteria used to select the most appropriate indicators. These quality criteria were heavily influenced by the works of [39,45,47].

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 [36]. A range of numbers of indicators was found in the literature, ranging from 55 split into five separate themes [42] to eight [41], dependent on geographical scale and data availability and quality. The authors in [39] suggest that an index should comprise a collection of indicators as small as possible.

Table 3. 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 [47], 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 [48].
Reliability	Whilst still available and measurable, the data must also be reliable so that the results are verifiable and cannot be contested. Credibility and data quality are vital aspects to index development [55].
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 [38,39]. 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 [55], similar to ELASTIC's requirement of isolatable impact [39].

The CARTI's indicator selection process selected a total of six indicators, three for each need and capacity element. Through a 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. These six CARTI indicators were selected based on, as a collection, sufficiently meeting the index goals in Table 3, and each passing a quality evaluation based on Table 3. These six indicators, their units and measurement methods are described in Table 4.

Table 4. Selected indicators and their measurement methods.

Element	Indicator	Units	Measurement Method
Need-based	Emissions and Pollutants	Annual tonnes of CO_2 per capita (tpppa)	Total annual road transport CO_2 emissions by local authority region derived from UK government data [70], 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 [71].
	Public Transport Access	Proportion of population outside walking distance of public transit stops (%)	GTFS data derived from UK government data [72] and GIS proximity methods using ESRI ArcGIS Pro determine the total population outside BREEAM recommended maximum walking distance of a bus stop [73,74], 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 [75].
	Government Investment (in transport)	Total investment per capita (£pp)	Total investment in transport and transport infrastructure divided by total population by local authority, derived from UK government data [76].
	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 [77].

3.5. CARTI Construction

Six indicators were selected, measured for each rural English local authority region, 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 straightforward comparison, and the calculation processes used to construct the index was designed to be clear to ensure its repeatability and useability by others [55].

For complete clarity, the CARTI was designed around a "one equation" index model [69]. Keeping the index calculation processes simple makes it easier for policy makers and the public to understand the CARTI, which was a key requirement.

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 4), the initial scoring was simple. For the remaining two indicators that outputted absolute alternatives (Emissions and Pollutants and Government Investment), the bisection method [78] scoring method 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 were 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.

By this method, the individual indicator score, Y, 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).

$$Y = 100 \times (X - X_{min})/(X_{max} - X_{min}) \tag{1}$$

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 [69]. 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 [64,65], in others, weights were applied based on the recurring popularity of an indicator in past literature [42,43]. 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 [47]. 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 [48,55]. Therefore, each CARTI indicator was weighted equally. Further, the bisection method used to score the indicators is ineffective when weighting criteria [65].

Given the maximum and minimum values for each indicator and Equation (1), each of the indicator values was 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. The bisection method used to score the indicators meant that the poorest-performing local authorities received a score of zero. Therefore, the arithmetic mean was used to generate need, capacity and potential index scores. This is a suitable method given that no weights are applied.

Figure 1 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.

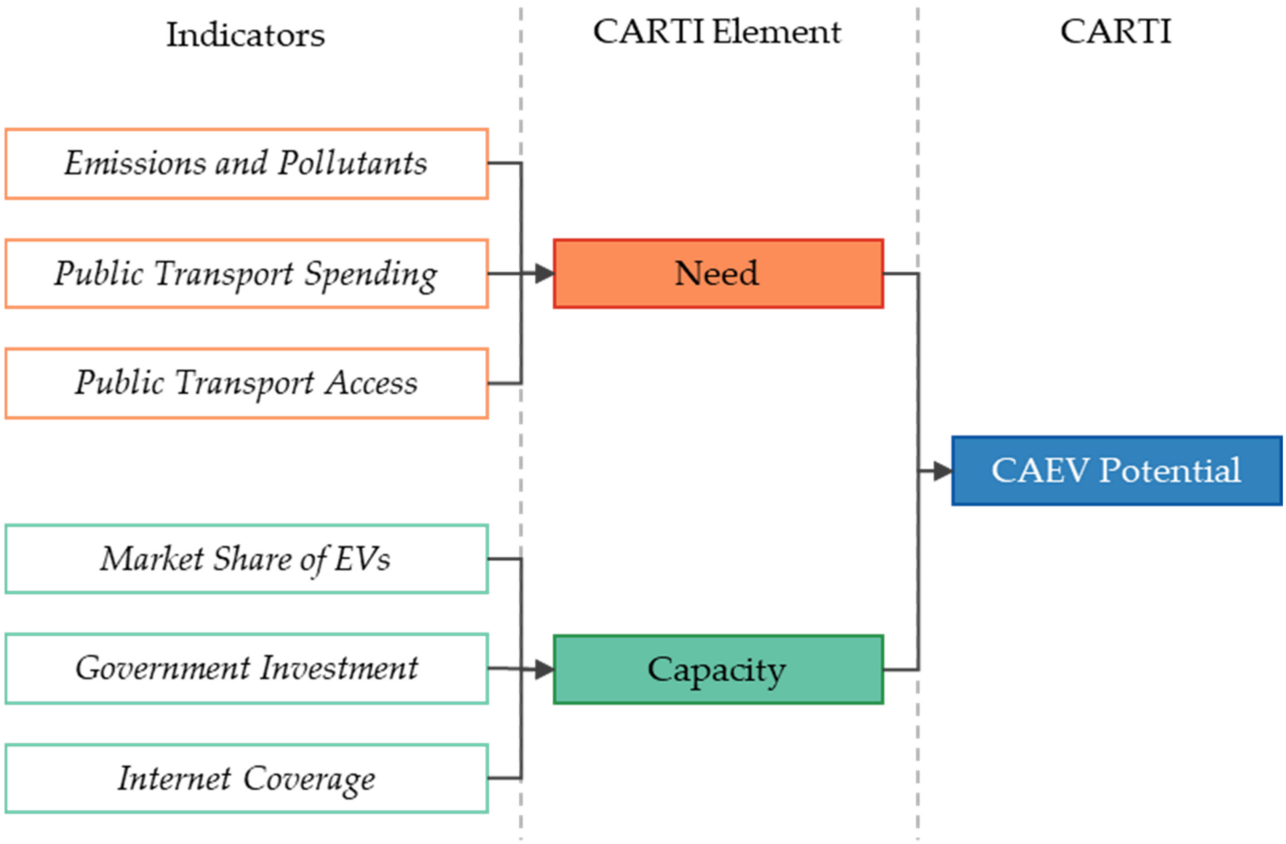

Figure 1. CARTI scoring levels.

This methodology has provided a detailed account of the reasoning and theory behind the development of the CARTI. In summary, a three-stage methodology was developed based on existing literature to create a dual-approach CARTI designed to meet goals that were driven by the research goals of this paper. 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 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 section. An evaluation into the CARTI's effectiveness at local authority and national levels is also described.

4. CARTI Application and Case Studies

Given the measurement methods described in Table 4, the CARTI results can be displayed spatially at the local authority level. As such, Figure 2 shows the need, capacity and total CAEV potential score results per rural local authority across the UK. The incorporation of spatial indicators, such as those selected for the CARTI, are useful for planning and policy processes, especially when the selected indicators need to be understood [46]. The contrasting depth of shades across (a) and (c) in Figure 2 shows a greater range of scores across the local authorities compared with (b). This visualisation highlights a greater range of disparity across rural need for CAEVs, against a more universally consistent capacity to support CAEV implementation. Therefore, the total CAEV potential is more influenced by the differences in the need-based CARTI element and its related indicator scores.

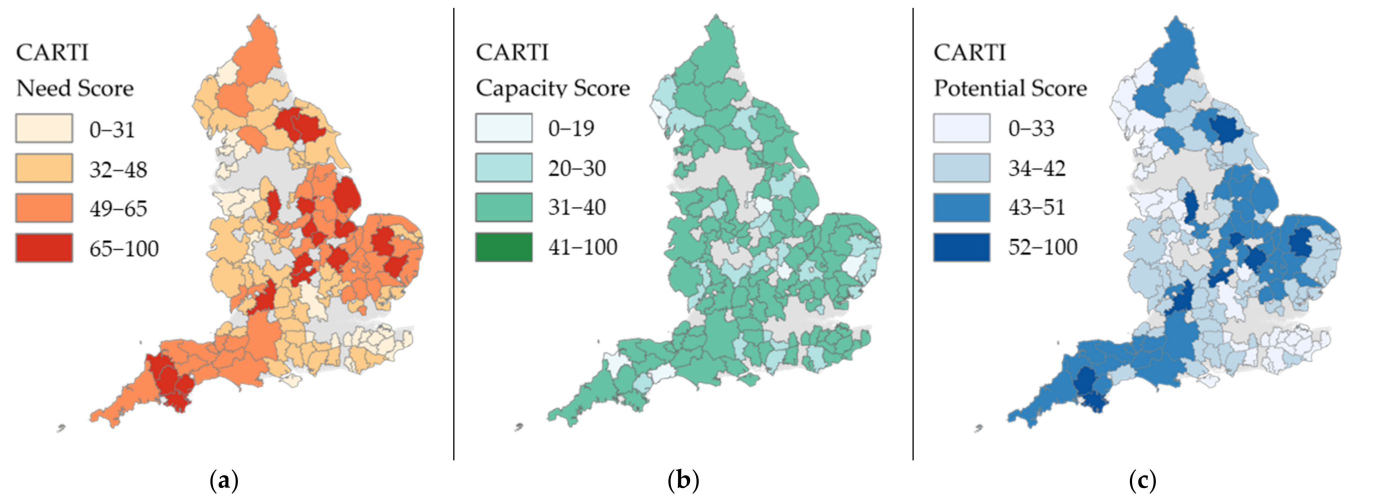

Figure 2. CARTI results. (**a**) Need Score, (**b**) Capacity Score, (**c**) Potential Score.

Based on the CARTI results in Figure 2, 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. In Figure 3, the Derbyshire Dales, South Lakeland and Isles of Scilly were selected based on their contrasting CARTI scores, geographical distribution, and due to transport and CAEV-related projects and trials occurring in these local authorities at the time of the study. A national perspective on the CARTI's use was also sought in a workshop with the Department for Transport's (DfT) Chief Scientific Advisor. Online workshops with these transport and planning professionals within the case study areas were carried out to establish their perspectives on the CARTI and its potential application within their respective regions. These workshops were conducted in accordance with the Declaration of Helsinki [79] and approved by the University of Nottingham Faculty of Engineering Ethics Committee, the results of which are reported in the following section.

Figure 3. Local authority case studies in England.

5. CARTI Validation

This discussion summarises the key findings from across the workshops undertaken to assess the CARTI. Given the methodological extent of indicator selection and CARTI development in this paper, this discussion mainly addresses whether the CARTI was a realistic and applicable planning tool for use in real-world transport planning and decision-making scenarios.

All workshop participants 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 geographic scale identifying specific cases for CAEV implementation might 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.

The relevance, quality and quantity of the selected CARTI indicators was debated with case study participants. 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.

Although Internet Coverage is a relevant indicator, the question was raised as to whether 4G technologies would be sufficient for rural CAEVs when 5th Generation (5G) wireless technologies offer greater speeds and reliability. However, the data rates and service capabilities of 4G mean that it is a critical technology for the operation of CAEVs [80,81], particularly in rural areas, where emerging high-speed 5G wireless technologies are unlikely to be established due to the short-range nature of 5G infrastructure, the sparseness of rural roads and populations [82] and its relative expense. Despite 5G being a potential necessity for SAE level 5 CAEVs, these vehicles may not be capable of navigating complex rural environments. If consistent and reliable, the 4G alternative is likely to be adequate to support level 3 and some level 4 rural autonomous vehicle operations and it is these scenarios that this paper is primarily concerned with.

It was suggested that the measurement of Personal Transport Spending needed further review, citing that expenditure on transport was more likely a sign of the extent of travel of a household, rather than the expense of their local transport systems. One suggestion was 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" across workshops, with one participant explaining that the indicator was not specific enough regarding in which areas of transport investment the investment was being spent. 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. Energy Capacity was identified as potentially more useful and references were made to the wider stability of charging infrastructure, rather than an indicator representing the number of EVs. In addition, it was 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, one of the most common talking points surrounding EVs in the transport industry was "whether people have off street parking or not and the charging issues associated with that". As such, an indicator measuring charging network extent and capacity was a common suggestion.

From a national perspective, it was suggested that there were two areas where an index such as the CARTI could be useful for national policy decision making. In both cases, the CARTI would only be acting as a single component of any decision-making process. The first way in which the CARTI could be used would be as an analytical approach to guide decisions regarding CAEV implementation. For each decision that 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. It was explained that, although already developed through scientific study, the CARTI would have to be scrutinised and refined by data specialists before its use in this way. This was because it is "really important, from a government point of view, that decision-making is transparent ... so having a good strong evidence base that enables and supports fair and equitable decision-making is always very helpful". These comments were supported by a participant from another workshop, who suggested that 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 would be its potential contribution to DfT strategies, such as the 2021 Transport Decarbonisation Plan [83]. "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". This is something that the CARTI was purposefully designed for. 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, the CARTI could be used to monitor progress on investment from the DfT and other sources. This idea was supported by an explanation that the CARTI would "be useful for the DfT if they were deciding about giving out grants" and using it to identify the most appropriate places for rural CAEV implementation based on the social and financial indicators that the CARTI uses. It was therefore suggested that the CARTI's most useful feature was its ability to identify specific local authorities and their attributes, which could be used to aid national decision making. However, again, it was stressed 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.

Following these discussions regarding the CARTI's practical use, 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 it would need to analyse and model the state of local authorities and their transport systems as CAEV technologies are implemented. 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 study workshops, where discussions included the integration of alternative and changing transport systems, including rail and unmanned aerial vehicles (UAV), and how the public 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. The need for the CARTI to integrate its methodology and indicator scores with other factors was a common suggestion. The need for a tool capable of integrating multiple transport modes such as public transport, private vehicles, rail systems and UAVs alongside road-based CAEV solutions was identified. Such integration of systems and modes is vital for future transport systems [19,57,84,85], and as a part of the solution, the CARTI must reflect this in its composition. A decision-making tool such as the CARTI, acting in a way similar to MaaS solutions by integrating transport modes, would be particularly useful for tourism and island community scenarios such as the Isles of Scilly. From a national perspective, the CARTI was identified as a tool "that you would want to see in the context of other information for example showing disposable income or ethnic diversity in an area for example". This would help to highlight additional contextual implementation challenges and whether any resulting CAEV implementation was potentially having a knock-on effect on other important policies. Measuring factors relating to tourists and their needs is an area that the CARTI does not currently 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 that is looking to address currently unsustainable transport models and systems, as demonstrated by both the South Lakeland and Derbyshire Dales case studies in particular. Further, reflecting on the importance of funding and economy, the CARTI could be an effective tourism-centric tool given the funding potential related to the tourism industry. This would also help to focus the application of the CARTI and provide an opportunity to reselect more specific indicators that meet the needs of tourist transport systems.

6. Conclusions and Limitations

Through the development and application of the CARTI, in this paper, the authors have made several contributions. Firstly, the need to support transport planners in addressing the unique challenges facing the rural implementation of CAEV technologies has been highlighted, 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 sustainability-based future transport measurement index. Finally, this paper 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.

The CARTI developed in this paper has shown potential to be a useful tool in the planning of rural-based CAEV transport systems. However, the CARTI has several limitations. Firstly, this research did not engage with professionals mid-way through the methodology, as suggested by the ELASTIC method [39]. Secondly, the measurement of each indicator was at a local authority level as a minimum due to a lack of data. Greater accuracies would be needed for transport planners to implement specific CAEV systems. Data availability also influenced the chosen methodology and the final results. Thirdly, the number of indicators that made up the CARTI was considered small, thereby limiting the CARTI's coverage and leaving out important aspects of rural and transport development. Finally, whilst perspectives were recorded regarding the potential of the CARTI across three case studies, the application did not go into enough depth. Specifically, the CARTI was not used by planners to make real CAEV-related decisions. This therefore limits the impact of the CARTI at this stage but will be explored in further work.

7. Further Work and Recommendations

Whilst established as a "good start", the CARTI remains in its infancy but showcases potential for use as a rural CAEV transport planning tool. As such, further work is needed to develop this potential. This can be done through further iterations of the CARTI's methodology and by adding more indicators to establish the correct balance between simplicity and measurement coverage. To do this, professionals should be engaged in the indicator selection steps of the CARTI's methodology and more extensive workshops should be run to assess the CARTI's application to real-world rural transport problems. As part of the CARTI's development, it would also be useful to conduct sensitivity analysis and comparison with similar indexes, such as the KPMG AVRI, to establish the effectiveness of this index and its indicators specific to local rural areas. To build on the research and findings in this paper, the authors recommend that the CARTI is applied to a greater range of case studies—in particular, expanding to assess UK local authority regions in Wales and Scotland, which feature sparse rural geographies. The CARTI could also be applied internationally to establish whether its data methods are applicable elsewhere. It is also recommended that a tourism-based version of the CARTI be considered, which would have greater clarity of purpose and potentially a greater pool of data to build on.

There is also a need for more effective engagement between the planning, research and transport industries to support future transport solutions, specifically in rural areas. Practical action, such as the development of rural-specific indexes similar to the CARTI, should be taken to ensure that rural communities do not lose out as they have historically done to urban-biased future transport technologies.

Looking to future directions in this research area, further work should include a more detailed look at the capabilities of SAE level 5 CAEVs in rural and complex remote environments, both addressing the autonomous technology itself and its potential for implementation regarding supporting infrastructure. One such infrastructure is that of 5G networks, which will likely be required to provide large quantities of information quickly and reliably to ensure that level 5 autonomous vehicles operate safely. As discussed in this paper, the terrestrial rollout of 5G networks is unlikely, providing an opportunity for low-Earth-orbit satellite (LEO) technology. LEOs are expected to provide indistinguishable global internet coverage between rural and urban areas. Rural areas may even benefit more from LEO satellites, with fewer obstructions compared to built-up urban environments [30]. Therefore, research is needed regarding the potential of the connectivity services from these LEOs and the integration of this connectivity with rural-based CAEVs.

Author Contributions: Conceptualisation, J.G.W.; Methodology, J.G.W.; Validation, J.G.W., S.M. and L.R.; Formal Analysis, J.G.W.; Investigation, J.G.W.; Data Curation, J.G.W.; Writing—Original Draft Preparation, J.G.W.; Writing—Review and Editing, J.G.W., S.M. and L.R.; Visualisation, J.G.W.; Supervision, S.M. and L.R.; Project Administration, J.G.W.; Funding Acquisition, J.G.W., S.M. and L.R. All authors have read and agreed to the published version of the manuscript.

Funding: The primary author is in receipt of a fully funded EPSRC Doctoral Training Grant studentship (grant number: EP/R513283/1).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the University of Nottingham Faculty of Engineering Ethics Committee by S03 on the 10th of November 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not yet publicly available as the primary author's PhD thesis has not yet been formally submitted. Further, the identities of this paper's research participants must be protected.

Acknowledgments: The primary author would like to acknowledge the financial support from the EPSRC, which has enabled this study. Thanks also go to each of the survey and interview participants for committing their time and insights to this research. Final thanks go to the primary author's supervisors, Stuart Marsh and Lucelia Rodrigues, for their support and contributions to this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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