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Smart transport: A comparative analysis using the most used indicators in the literature juxtaposed with interventions in English metropolitan areas

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ABSTRACT

The development of smart transport technologies, methods, strategies and infrastructures has drawn much attention in recent years, owing to the rise of smart cities paradigms and the rapid technological advancements in the transport sector. New transport technologies create opportunities and challenges for English cities to move towards a more sustainable and integrated future. Smart governance and interventions in the English metropolitan areas are reviewed to provide a background of the smart city and transport development in the UK.

Despite the increasing commercial and political attention, there is still a lack of understanding and proposals for a robust framework to evaluate the smart transport system. It is challenging to build a toolbox that suits both academics and practitioners when developing transport interventions and investments. This paper proposes a comprehensive and up-to-date framework to assess smart transport development in cities. A systematic literature review is conducted to identify the most used indicators and important indices. New indicators that illustrate trending themes are added to the existing toolbox. In total, 49 indicators are listed in this study, including five new ones. We also show several aspects and the overall performance in the new evaluation framework by aggregating indicators into indices in the following groups: 1) private, public and emergency transport indices; 2) accessibility, sustainability and innovation indices; and 3) a composite index. The new evaluation framework is applied in eleven English metropolitan areas. The empirical results show that Greater London has the best development in smart transport, followed by West Midlands and West of England. The findings can provide useful insights for metropolitan authorities and their transport authorities when key devolution strategies are in place and substantial investment packages are considered.

Introduction

"Smart city" is a popular label used by cities worldwide and is gradually becoming a leading paradigm of urbanism (Kunzmann, 2014, Bibri and Krogstie, 2020). Smart city products and interventions make use of innovations to enhance sustainability and quality of lives. The smart transport system is an essential part of the concept and operations in a smart city. Technological innovation has permeated this sector for decades, allowing smart transport to be a priority in smart city development. "Smart" in the transport sector can refer to new propulsion (e.g., electricity), new vehicle controls (e.g., Intelligent Transport System), new business models (e.g., car-sharing), new regulatory, and new transport planning and policies. Their main objectives are reducing pollution, reducing traffic congestion, increasing safety, improving transfer speed and reducing travel costs (Benevolo et al., 2016). However, the emergent technology itself and the changing travel patterns caused by smart transport innovations are highly uncertain and complex. The advanced technology and proper governance should enhance smart transport development with added value (Docherty et al., 2018). Transport governance can impact the development of smart transport. In smart cities, smart transport governance contains a set of schemes, policies, projects and actions. These interventions can include integrated ticketing, electric vehicles, automated vehicles, and clean transport policies (Woods et al., 2017). Thus, it is necessary to evaluate and analyse the smart transport developments in terms of technologies, methods, infrastructure and interventions.

The UK has a long history of developing smart transport by applying new technologies and planning for smart future mobility. For example, the UK Department for Transport (DfT) developed a pioneering travel information service, Transport Direct, in the early 2000s (Dft, 2017). The UK's overall policy aims to be a world leader in Intelligent Transport Systems (ITS) (Dft, 2017). Transport innovations,

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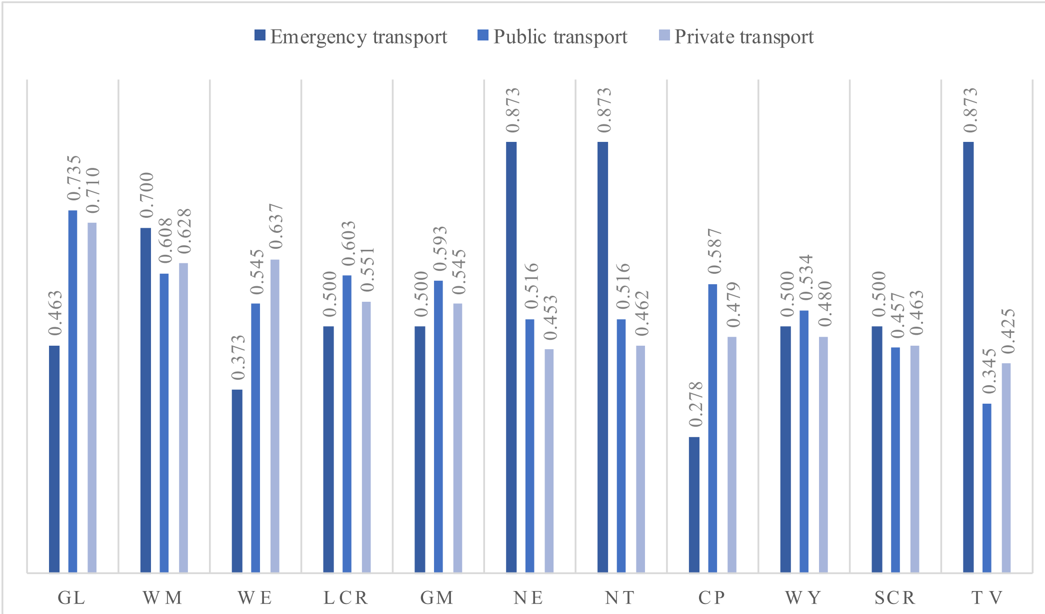

Fig. 1. Results of different transport systems.

including integrated information, cleaner vehicles and infrastructure, are highlighted in many cities' latest transport plans. Transport authorities such as Transport for London are actively preparing for smart future mobility (GO-Science, 2019). Therefore, it is worth investigating the development of smart transport in UK cities.

One way of measuring smart transport is through indicators, indices, and a composite index. An indicator or index can represent a specifically evaluable phenomenon through proper measurements (Lopez-Carreiro and Monzon, 2018), making it a powerful tool to describe complex phenomena and support decision-making processes (Kitchin et al., 2015, Battarra et al., 2018a). Many studies and some international standards organisations have proposed indicators to benchmark smart transport as part of the smart city index. Despite many indicators and indices to assess the smart city, less work has been done to evaluate the smart transport system and compare smart transport in different areas. A comprehensive and up-to-date framework with a holistic set of indicators/indices to measure various aspects in the smart transport system is necessary (Anthopoulos et al., 2019; Yousif and Fox, 2018; Battarra et al., 2018ab).

The new evaluation framework is built on the previous highly cited research by Debnath et al. (2014), Garau et al. (2016), Pinna et al. (2017), Lopez-Carreiro and Monzon (2018) as well as Battarra et al. (2018a). We reviewed articles on smart transport indicators/indices and selected the most used indicators to represent important variables in smart transport. This study further supplies the existing list of indicators with new indicators that can reveal trending topics. We then synthesise the individual indicators into three groups to reflect specific aspects and the overall development. Firstly, indicators in the private, public and emergency transport sub-systems are aggregated into private transport index, public transport index and emergency transport index, respectively. Secondly, the individual indicators are synthesised into accessibility, sustainability and innovation indices, which are the most common aggregated indices in the literature. Lastly, the accessibility, sustainability and innovation indices are further combined into a composite index - the smart transport index, showing the overall development of smart transport in a city. The indicators, indices and composite index are applied in the case study in English metropolitan areas, specifically Combined Authorities (CAs) and Greater London.

In this research, we first discuss the smart city and transport development, with a special focus on their governance and interventions, in the English metropolitan areas. This sub-regional spatial scale is suitable for the analysis of transport networks and the governance structures in the sub-regional tier can have strong impacts on transport development. We then review the most commonly used indicators and indices in analysing smart transport. Based on the review, a new evaluation framework containing important individual indicators and aggregated indices is constructed for our empirical study. The new framework is applied to the selected English metropolises, allowing us to compare the smart transport developments in the current CAs and the GLA. This paper raises three research questions:

1) How do the English metropolises govern smart transport in terms of interventions?
2) What are the most common and important indicators and indices to examine smart transport?
3) What are the smart transport developments in the English metropolises?

To answer the questions, we have organised this paper as follows: Section 2 presents the smart city and smart transport features in English metropolitan areas; Section 3 outlines the methods of indicator selection and index construction for this paper; Section 4 discusses smart transport results using our proposed evaluation framework in the selected cases; Section 5 extensively discusses the linkages among smart transport development, indices, and interventions as well as the implication for smart transport interventions; Section 6 concludes the results and discusses further research directions.

Smart city and smart transport in English metropolitan areas

Overview of English metropolitan areas (CAs and GLA)

A metropolitan area usually contains a core area with a substantial population and adjacent districts. The core city and the surrounding areas are spatially, socially and economically linked (Hall, 2009).

Combining the resources in a metropolitan area can accelerate urban development and enhance the local and regional transport systems (Fenwick and Johnston, 2020). This study uses the metropolitan scale because the transport network can be comprehensively analysed at this scale. The government authority at this scale can effectively operate economies and transport systems through clear policy interventions (Marsden and Docherty, 2019, National Audit Office, 2017).

In England, Combined Authorities (CAs) are built at the metropolitan scale with devolution powers, aiming to accelerate economic developments and improve transport networks outside London (Lorencka and Obrebska, 2018). Similar powers and autonomy to the London Mayor and Greater London Authority (GLA) are given to CAs. CAs can coordinate the resources and interventions in their areas. Although different CAs have their priorities and strategies, transport is one of the main concerns of all CAs. They wield power over the local road network, bus franchising, and the smart and integrated ticketing system. The administrative authorities can regulate the smart transport providers to ensure the new products are accountable and guarantee added value to the cities. Local and sub-regional authorities can steer their smart transport development towards a socially, environmentally and economically sustainable direction by actively inventing future mobility (Moscholidou and Pangbourne, 2019).

The first CA was Greater Manchester Combined Authority in 2011, followed by four CAs (i.e., North-East, Liverpool City Region, Sheffield City Region and West Yorkshire) in 2014 (Sandford, 2019a). In designing CAs, policymakers followed the concept of "city region", which indicated that combined authorities have strongly relied on their core cities (Hickman and While, 2017). An exception to previous city regions in the CAs is Cambridgeshire and Peterborough (Hickman and While, 2017). Although it is not a typical metropolitan area, this study keeps it for comparison. Ten CAs to date (May 2020) are used as English metropolitan areas in this study.

When comparing CAs, the GLA is often used as a beacon [e.g. (Sandford, 2019b)]. The GLA can be seen as the first successful "combined authority". It was formed in 2000 (the first mayoral election), bringing the collaboration of 33 local authorities (Hickman and While, 2017, Townsend, 2019). GLA is an example of devolution and the mayor holds powers to promote urban and transport developments within London (Sandford, 2018). Transport for London (TfL), chaired by the mayor, is in charge of delivering transport such as the London Underground, buses, trams, taxis and private hire vehicles. It should be noted that the GLA is a unique authority and it is fundamentally different from the CAs. The mayor of London and GLA were created by different legislation and were given different powers (Fenwick and Johnston, 2020). Nevertheless, London is the most important metropolis in the UK. Thus, we choose the ten CAs and the GLA as cases of metropolitan areas to illustrate the development of smart transport in metropolitan areas.

The English metropolitan areas are heterogeneous in population, areas and social-economic development (as shown in Table A1, Appendix). Greater London (GL) has the largest population, density, and total gross value added (GVA). Greater London is the sole first-tier metropolis. Considering both population and total GVA, the second-tier large metropolises are West Midlands, Greater Manchester, West Yorkshire, and Liverpool City Region. The remaining metropolises either have smaller populations or worse economic performance. The social-demographic information has been considered when constructing the indicators and analysing the results.

Smart city developments in CAs and GLA

Smart cities in the UK can be categorised into four groups: leaders, contenders, challengers and followers, according to the latest UK smart city report (Woods et al., 2017). The core cities/primary local authority in the metropolitan areas are ranked in this report. Bristol in West of England and London are the leaders. Manchester in Greater Manchester, Birmingham in West Midlands, Leeds in West Yorkshire, Peterborough and Cambridge in Cambridgeshire and Peterborough, and Newcastle in North of Tyne are the contenders. Sheffield in Sheffield City Region and Liverpool in Liverpool City Region are challengers (Woods et al., 2017). In each core city, the main innovation areas vary. Bristol leads on the Internet of Things while London is ahead in Data and Analytics. One of the notable data sources in London is the Department for Transport. Leeds is a model of innovative health, whereas Peterborough is the pioneer in sustainability. Newcastle has focused on smart education (Woods et al., 2017).

A smart city is more than smart technologies, but digital possibilities in the cities lie at the core of the smart city characteristics (Lyons, 2018; Woods et al., 2017). To simplify the policy reviewing process, the smart interventions in this study refer to policies or projects that can use digital technologies or accelerate the deployment of modern technologies. The ongoing smart city interventions in metropolitan areas are identified and listed in Table 1. For each metropolitan, all interventions listed in their official websites are collected. As a collective notion, interventions contain policies, programmes[1], packages[2], projects and schemes[3] (Hills and Junge, 2010).

West of England has six main interventions, focusing on the economy and business, transport and energy. Great London Authorities have an extensive list of smart interventions, the most important of which is "Smart London Together", which is the mayor's roadmap to make London the smartest. London's interventions cover many areas; the key areas are transport, sustainability, health, energy, economy and business, and data and analytics.

Greater Manchester has many main projects in its Digital Strategy, with special focuses on economy and business, health, data and analytics, transport, and sustainability. West Midlands has the main industrial strategy and five smart projects, targeting the economy and business, transport, the Internet of Things and sustainability. Eight ongoing smart interventions are found in West Yorkshire, where the principal areas are economy and business, transport and sustainability. Cambridgeshire and Peterborough Combined Authority has three initiatives and two proposed smart transport packages/schemes. The key areas are sustainability as well as the economy and business. Two programmes aiming at economy and business are seen in North of Tyne.

Concentrating on economy and business, Sheffield City Region has three smart interventions. Liverpool City Region has a range of action plans related to smart city development, and its key areas cover economy and business, sustainability, and transport. Two interventions focusing on the economy and business as well as sustainability are seen in North East Combined Authority. Tees Valley has several smart city projects, mainly in the areas of economy and business.

Generally, the most interventions can be found in areas with a high ranking smart core city, as shown in Table 1. West of England, Greater London, Greater Manchester, and West Midlands have more policies, schemes, and projects, with more key areas than other CAs. In terms of key areas, the economy and business are the most common focus of all authorities, followed by sustainability and transport. Transport is one of the key areas in West of England, Greater London, Greater Manchester, West Midlands, West Yorkshire and Liverpool City Region.

Smart transport governance and interventions in CAs and GLA

Smart transport/mobility is one of the six main elements in a smart city, aiming to enhance accessibility, sustainability, safety and other factors (Giffinger et al., 2007). A smart transport system incorporates such elements as infrastructure, travel means, products, business mod-

[1] A series of similar schemes to achieve an overarching policy objective.

[2] A set of measures to address common objectives.

[3] An individual measure for a specific problem.

Table 1
Smart city interventions.

Authorities	Ongoing smart interventions	Key areas	Smart core city ranking and category
West of England	**Regional Public Transport** 5G Smart Tourism Future Bright Women into Digital Jobs, Education and Training programme Creative Scale Up Clean Growth	Economy and Business **Transport** Energy	1 Leader
Greater London	**Smart London Together** London Datastore, TfL open data portal, police interactive dashboard CleanTech, FLexLondon, Energy for Londoners Smart Sustainable Districts **Smart Mobility Living Lab,** etc.	**Transport** Sustainability Energy Health Economy and Business Data and Analytics	2 Leader
Greater Manchester	Digital Strategy: Early Years Digitisation, Integrated Digital Healthcare Record, Greater Manchester Information Sharing Strategy, **Smart Ticketing**, Greater Manchester Cyber and Resilience, Made Smarter and Digital Enablement Services, ERDP-funded digital initiatives, Annual digital creative and tech festival, etc Digital Response to Covid19, the Greater Manchester Tech Fund Smart Energy project: Smart Heat project	Economy and Business Health Data and Analytics **Transport** Sustainability Energy	3 Contenders
West Midlands	West Midlands Industrial Strategy Digital Retraining scheme 5G Testbed Energy Innovation Zones **Midlands Future Mobility** **Mobility Credits Pilot**	Economy and Business **Transport** Internet of Things Sustainability	4 Contenders
West Yorkshire	Growing business: Connecting Innovation Clean energy and Environmental Resilience: **Ultra-Low Emission Vehicle (ULEV) Taxi Scheme, Clean Bus Technology Fund**, Energy Accelerator **West Yorkshire-plus Transport Fund: Rail Park & Ride Programme, The Temple Green Park & Ride** **The Leeds Public Transport Investment Programme: LPTIP Real Time Programme** **Local Transport Plan and Other DFT Funding: CCTV Revenue saving**	Economy and Business **Transport** Sustainability	5 Contenders
Cambridgeshire and Peterborough	**Future Mobility Zone (propose)** **Cambridgeshire autonomous metro (draft)** Eastern Agri-Tech Growth Initiative Growth Hub Projects Digital Sector Strategy	Sustainability Economy and Business	9 Contenders10 Contenders
North of Tyne	STEM and Digital Skills Programme Inclusive Economy Innovation Fund: Employability and Skills Programme	Economy and Business	14 Contenders
Sheffield City Region	Knowledge Gateway AMRC Light weighting Centre Local Growth Fund: Barnsley's Digital Media Centre	Economy and Business	16 Challengers
Liverpool City Region	Adult Education Budget (digital skills) Skills for Growth Action Plan: Innovation Action Plan 2018–2020, Digital and Creative Action Plan 2018–2020, Skill Strategy 2018–2023, Health & Care Action Plan 2018–2020, Low Carbon Action Plan 2018–2020, Advanced Manufacturing Action Plan 2018–2020 Strategic Investment Fund: **Train Connectivity and Information Systems, Smart Ticketing business case**	Economy and Business Sustainability **Transport**	18 Challengers
North East	Strategic Economic Plan (smart specialisation) Go Ultra Low North East	Economy and Business Sustainability	–
Tees Valley	BoHo 'The Digital City' Hartlepool College of Further Education – Telecare and Electric Vehicle Skills Enhancement Hartlepool Centre of Excellence in Technical Training for the Creative Industries Inspiring our Future	Economy and Business	–

els, operation system and interventions. Smart mobility considers the delivery of people, data and goods. In this research, we focus on transporting people within metropolitan areas.

In English metropolitan areas, most of the CAs are responsible for the transport systems and their services. In the devolution deals, combined authorities and mayors have transport-related powers such as leading the transport plan. However, North of Tyne, which is separate from the North East Combined Authority, does not have new transport powers in its devolution deal[4]. The preeminent intervention in North East was published in 2016, before the establishment of North of Tyne, and it covers the areas of the current North of Tyne and North East combined authorities.

Greater London, West Midlands, and Greater Manchester have their unique government body responsible for regulating the transport system and coordinating transport services. Transport for London (TfL) was created in 2000. It runs the day-to-day transport operations, including buses, the undergrounds and taxis, and it manages the transport infrastructure in Greater London. It is known as an internationally leading transport body (GO-Science, 2019, White, 2016). Following TfL's success, Transport for Greater Manchester was built in 2011 and Transport for West Midlands was founded in 2016, with similar powers to TfL and aiming to deliver London-style plans.

[4] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/754719/North_of_Tyne_Deal.pdf.

Table 2
Smart transport interventions.

Authorities	Transport authorities	Main transport interventions	Smart aspects	Main Objectives
Greater London	Transport for London	Mayor's Transport Strategy 2018[1]	Communication, Smart Information, Smart Ticketing, CAV, Sharing Services, Smart Logistics Delivery, Cleaner Vehicles and Infrastructure, Open Data, Smart Parking	Accessibility, Sustainability, Innovation
West Midlands	Transport for West Midlands	Movement for Growth: The West Midlands Strategic Transport Plan[2]	Smart Information Systems, Maas, Open Data, Clean Air Zone, Intelligent Traffic Management, Smart Logistics Delivery, Smart Road Safety, Sharing Service, Smart Motorways, Smart Ticketing, CAV	Accessibility, Sustainability, Innovation
West of England	WECA	Joint Local Transport Plan 2020–2036[3]	CAV, Maas, Open Data, Smart Motorway, Intelligent Traffic Management, Smart Information, Cleaner Vehicles and Infrastructure, V2I[4] Communication, Smart Logistics Delivery, Smart Ticketing, Sharing Services	Accessibility, Sustainability, Innovation
Greater Manchester	Transport for Greater Manchester	GM Transport Strategy 2040[5]	Maas, Smart Information, Smart Ticketing, Cleaner Vehicles and Infrastructure, Sharing Services, Smart Vehicles (CAV), Smart Signal, Smart Traffic Control, Smart Motorway, Open Data	Accessibility, Sustainability, Innovation
Liverpool City Region	LCRCA	LCRCA transport plan[6]	Smart Ticketing, On-Demand Bus Service, Cleaner Vehicles and Infrastructure	Accessibility, Sustainability
North of Tyne	NTCA[7] & NECA	–	–	–
West Yorkshire	WYCA	Transport Strategy 2040[8]	Smart Ticketing, Smart Motorway, Smart Information, Open Data, Intelligent Traffic Management, Maas, CAV, Sharing Services	Accessibility, Sustainability, Innovation
Cambridgeshire and Peterborough	CPCA	Local Transport Plan[9]	Smart Motorway, Smart Information, Smart Infrastructure (Autonomous Metro), Cleaner Technology, Smart Parking	Accessibility, Sustainability
North East	NECA	Transport Manifesto[10]	Smart Ticketing, Smart Information, Cleaner Vehicles and Infrastructure, Intelligent Traffic Management, Sharing Services	Accessibility, Sustainability
Sheffield City Region	SCRCA	SCR Transport Strategy[11]	Maas, Smart Ticketing, Smart Motorway, CAV, Smart Logistics Delivery, Smart Information	Accessibility, Sustainability
Tees Valley	TVCA	Strategic Transport Plan[12]	Cleaner Vehicles and Infrastructure, Smart Information, Smart Ticketing, Maas, CAV	Accessibility, Sustainability

[1] https://www.london.gov.uk/what-we-do/transport/our-vision-transport/mayors-transport-strategy-2018.
[2] https://www.tfwm.org.uk/strategy/movement-for-growth/.
[3] https://travelwest.info/projects/joint-local-transport-plan.
[4] Vehicle to infrastructure.
[5] https://tfgm.com/2040.
[6] https://www.liverpoolcityregion-ca.gov.uk/governance/policy-documents/.
[7] No new transport powers in devolution deal. A new transport committee working with NECA.
[8] https://www.westyorks-ca.gov.uk/media/2379/transport-strategy-2040.pdf.
[9] https://cambridgeshirepeterborough-ca.gov.uk/about-us/programmes/transport/ltp/.
[10] https://northeastca.gov.uk/what-we-do/transport/.
[11] https://d2xjf5riab8wu0.cloudfront.net/wp-content/uploads/2019/03/SCR_Transport_Strategy_11.04.2019.pdf.
[12] https://teesvalley-ca.gov.uk/transport/strategic-transport-plans/.

Apart from the smart transport interventions listed in Table 1, we also review the main ongoing transport policies in each case to see if the main transport policy mentions smart transport. The mentioned smart aspects are identified, and the key themes (e.g., accessibility, sustainability and innovation) in the objectives are listed in Table 2.

Each authority has its main transport intervention, and all of the documents mentioned some smart transport elements. Most of the transport plans have a separate chapter discussing the new technologies and smart mobility possibilities. Thus, most of the interventions have the main objectives of innovation. Smart ticketing, smart information, and cleaner vehicles and infrastructure (e.g., electric cars and electric charging devices) are the most commonly highlighted smart elements in the main transport interventions. Other smart aspects, including smart logistic delivery, smart parking, open data, CAV and MaaS, are also mentioned in many documents, mainly discussing the potential impacts of coming technologies.

Generally, all transport authorities in the English metropolitan areas admit that smart technologies can influence future mobility and transport systems and they need to prepare for the potential changes. The main challenge is that smart technologies are highly uncertain in the transport sector are highly uncertain regarding their evolution and potential impacts. Although all authorities are preparing future mobility, transport planners and policymakers cannot plan for the new smart transport products or business models because many future scenarios are possible. Thus, an evaluation framework with good indicators to illustrate the current situations and future potentials of a city's smart transport can provide meaningful insights.

Methodology

Indicators, indices and a composite index have been used in many studies to measure the performance of urban systems such as the transport sector (Giffinger and Pichler-Milanović, 2007, Battarra et al., 2018a, Battarra et al., 2018b, Debnath et al., 2014, Kitchin et al., 2015). This study uses a four-step method to construct the index system. We first reviewed the international standard organisations for smart city/transport documents and scientific studies in Web of Science, Scopus and Google Scholar that used indicators or an index to evaluate smart transport. Secondly, we build an appropriate set of indicators for our case studies based on the systematic literature review. Thirdly, six synthetic indices are calculated from the selected indicators in each subset. To illustrate different sub-systems, we aggregated the indicators into public, private and emergency transport indices. Categorised by important pillars in smart transport, indicators are also aggregated into accessibility index, sustainability index, innovation index and smart transport index. Finally, this study also presents a composite index, namely the smart transport index.

Measuring smart transport through indicators and indices

The keywords of "smart transport/transportation/mobility" and "index/indicator" are applied when searching for the relevant documents in International Organisation for Standardization and academic databases of Web of Science, Scopus and Google Scholar. The search returns 301 articles, and a bibliometric analysis is conducted (Aria and Cuccurullo, 2017). Irrelevant documents, including articles that do not contain indicator/index, studies focusing on other smart features (e.g., smart environment), measurements only on a specific aspect of smart mobility (e.g., road maintenance, walkability) and full-text articles unavailable to access online, are removed in the screening process. After screening, 39 publications are left, and these articles are used for choosing indicators. Ranking by total citations per year, the most highly cited manuscripts, as the sample reviewed articles, are listed in Table A2 in the Appendix.

More than 50 different indicators have been used to describe various aspects of the smart transport system, covering the themes of accessibility, service, safety, technological integration and equity. We identified 30 most used indicators, as listed in Table 3. The indica-

Table 3
Most used indicators in reviewed articles.

Indicators	Sources	Themes
Public transport supply/service	(Battarra et al., 2018a,b; Das, 2020; Garau et al., 2015, 2016; Indrawati et al., 2017; Li et al., 2019; Lopez-Carreiro and Monzon, 2018; Miguel et al., 2018; Ogrodnik, 2020; Petrova-Antonova and Ilieva, 2018; Pinna et al., 2017; Lerner et al., 2011; Pop and Proştean, 2019; Shaheen et al., 2019; ISO 37122:2019;)	Accessibility
Low-emission vehicles	(Bakogiannis et al., 2019; Battarra et al., 2018a,b; Benevolo et al., 2016; Das, 2020; Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018; Miguel et al., 2018; Mol, 2018; Petrova-Antonova and Ilieva, 2018; Pinna et al., 2017; Yigitcanlar et al., 2020; Zapolskyte et al., 2020; Zong et al., 2019; Pop and Proştean, 2019; Shaheen et al., 2019; ISO 37122:2019;)	Sustainability
Integrated and electronic ticketing system	(Aleta et al., 2017; Battarra et al., 2018a,b; Benevolo et al., 2016; Debnath et al., 2014; Garau et al., 2015, 2016; Longo et al., 2019; Lopez-Carreiro and Monzon, 2018; Petrova-Antonova and Ilieva, 2018; Pindarwati and Wijayanto, 2015; Zapolskyte et al., 2020; Zong et al., 2019; Pop and Proştean, 2019; ISO 37122:2019)	Innovation
Cycling lane	(Battarra et al., 2018a,b; Benevolo et al., 2016; Garau et al., 2015, 2016; Miguel et al., 2018; Mol, 2018; Ogrodnik, 2020; Orlowski and Romanowska, 2021; Petrova-Antonova and Ilieva, 2018; Pinna et al., 2017; Zapolskyte et al., 2020; Pop and Proştean, 2019; ISO 37120:2018)	Sustainability, Accessibility
Bike-sharing	(Balducci and Ferrara, 2018; Battarra et al., 2018a,b; Benevolo et al., 2016; Braga et al., 2019; Garau et al., 2015, 2016; Mol, 2018; Petrova-Antonova and Ilieva, 2018; Pinna et al., 2017; Zapolskyte et al., 2020; Lerner et al., 2011; Pop and Proştean, 2019; ISO 37122:2019;)	Sustainability, Innovation
Car-sharing	(Balducci and Ferrara, 2018; Battarra et al., 2018a,b; Benevolo et al., 2016; Garau et al., 2015, 2016; Li et al., 2019; Mol, 2018; Petrova-Antonova and Ilieva, 2018; Zapolskyte et al., 2020; Lerner et al., 2011; Pop and Proştean, 2019; ISO 37122:2019)	Innovation, Accessibility
Mode choice	(Das, 2020; Dudzevičiūtė et al., 2017; Indrawati et al., 2017; Li et al., 2019; Lopez-Carreiro and Monzon, 2018; Mol, 2018; Orlowski and Romanowska, 2021; Petrova-Antonova and Ilieva, 2018; Yigitcanlar et al., 2020; Zong et al., 2019; Lerner et al., 2011; Pop and Proştean, 2019; Shaheen et al., 2019; ISO 37120:2018)	Accessibility
Modern parking solutions	(Battarra et al., 2018a,b; Benevolo et al., 2016; Debnath et al., 2014; Garau et al., 2015, 2016; Mol, 2018; Pinna et al., 2017; Wibowo and Grandhi, 2015; Zapolskyte et al., 2020; Pop and Proştean, 2019; ISO 37122:2019)	Innovation
Traffic coordination/operation system	(Aleta et al., 2017; Benevolo et al., 2016; Debnath et al., 2014; Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018; Mol, 2018; Orlowski and Romanowska, 2021; Pindarwati and Wijayanto, 2015; Wibowo and Grandhi, 2015; Zapolskyte et al., 2020; Pop and Proştean, 2019)	Innovation
Real time travel planner	(Battarra et al., 2018a,b; Benevolo et al., 2016; Debnath et al., 2014; Garau et al., 2015, 2016; Mol, 2018; Petrova-Antonova and Ilieva, 2018; Pindarwati and Wijayanto, 2015; Zapolskyte et al., 2020)	Innovation
Travel time	(Abu-Rayash and Dincer, 2020; Indrawati et al., 2017; Longo et al., 2019; Lopez-Carreiro and Monzon, 2018; Miguel et al., 2018; Petrova-Antonova and Ilieva, 2018; Lerner et al., 2011; Shaheen et al., 2019; ISO 37120:2018)	Accessibility
Restricted/special traffic zones	(Battarra et al., 2018a,b; Benevolo et al., 2016; Debnath et al., 2014; Petrova-Antonova and Ilieva, 2018; Pindarwati and Wijayanto, 2015; Wibowo and Grandhi, 2015; Zapolskyte et al., 2020; Pop and Proştean, 2019)	Sustainability
Intelligent traffic light/Smart street lighting	(Balducci and Ferrara, 2018; Battarra et al., 2018a,b, Garau et al., 2015, 2016; Mol, 2018; Zapolskyte et al., 2020; ISO 37122:2019)	Innovation
Mobile phone apps	(Aleta et al., 2017; Battarra et al., 2018a,b; Das, 2020; Garau et al., 2015, 2016; Liu et al., 2019; Orlowski and Romanowska, 2021; Pop and Proştean, 2019)	Innovation
Public transport demand	(Battarra et al., 2018a,b, Garau et al., 2015, 2016; Li et al., 2019; Lopez-Carreiro and Monzon, 2018; Petrova-Antonova and Ilieva, 2018; Pinna et al., 2017; Pop and Proştean, 2019)	Accessibility
Variable message sign	(Battarra et al., 2018a,b; Benevolo et al., 2016; Garau et al., 2015, 2016; Zapolskyte et al., 2020; Pop and Proştean, 2019)	Innovation
In-vehicle technologies: AVL, CCTV, detection, GPS	(Battarra et al., 2018a,b; Debnath et al., 2014; Mol, 2018; Pindarwati and Wijayanto, 2015; Zapolskyte et al., 2020; ISO 37122:2019)	Innovation
Pedestrian zones	(Balducci and Ferrara, 2018; Battarra et al., 2018a,b; Benevolo et al., 2016; Mol, 2018; Zapolskyte et al., 2020; Pop and Proştean, 2019)	Sustainability, Accessibility
Road fatality rate	(Bakogiannis et al., 2019; Das, 2020; Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018; Ogrodnik, 2020; Shaheen et al., 2019; ISO 37120:2018)	Sustainability
Private transport supply	(Indrawati et al., 2017; Ogrodnik, 2020; Orlowski and Romanowska, 2021; Salvia et al., 2016; Lerner et al., 2011; ISO 37120:2018)	Accessibility
Autonomous Vehicles	(Benevolo et al., 2016; Kelley et al., 2020; Mol, 2018; Zapolskyte et al., 2020; ISO 37122:2019)	Innovation
Sustainable mobility plans/ measures/investment	(Aleta et al., 2017; Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018; Orlowski and Romanowska, 2021; Zapolskyte et al., 2020)	Sustainability
Electronic bus stop signs	(Battarra et al., 2018a,b, Garau et al., 2015, 2016; Zong et al., 2019; Pop and Proştean, 2019)	Innovation
Electric charging devices	(Abu-Rayash and Dincer, 2020; Benevolo et al., 2016; Mol, 2018; Petrova-Antonova and Ilieva, 2018; Zapolskyte et al., 2020)	Sustainability
Mobility difficulties	(Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018; Miguel et al., 2018; Shaheen et al., 2019)	Accessibility
Internet access/services	(Das, 2020; Liu et al., 2019; Orlowski and Romanowska, 2021; Petrova-Antonova and Ilieva, 2018)	Innovation
Park and ride	(Balducci and Ferrara, 2018; Ogrodnik, 2020; Zapolskyte et al., 2020)	Innovation
Air quality	(Bakogiannis et al., 2019; Lerner et al., 2011; Shaheen et al., 2019)	Sustainability
Road transport energy consumption	(Indrawati et al., 2017; Mol, 2018)	Sustainability
Travel cost	(Indrawati et al., 2017; Lopez-Carreiro and Monzon, 2018)	Accessibility

tors that have been used more than ten times are low-emission vehicles (17), public transport supply/service (16), integrated and electronic ticketing system (15), cycling lane (14), bike-sharing (14), mode choice (14), car-sharing (13), modern parking solutions (12), traffic coordination/operation system (11), and real-time travel planner (10). Indicators with fewer than two citations are removed.

In the reviewed papers, most indicators are one of two types: measurable indicators such as the number of vehicles, and "on and off" indicators such as whether a city has travel ticketing online (e.g., 0 for no travel ticketing online and 1 for a city with online ticketing). In calculating the index, most of the authors used the rescaling method in normalisation (e.g., Min-Max normalisation) and equal weighting in aggregating individual indicators. Most of the indices are calculated by the geometric or arithmetic means of different variables.

Authors usually classify indicators into several subsets and each subset indicates an important aspect of smart transport. Indicators in each subset are often aggregated into an index to illustrate an aspect. In classifying indicators, Debnath et al. (2014) analysed smart transport in the three categories of private transport, public transport and emergency transport. Battarra et al. (2018a) used ICT, sustainability and accessibility variables to evaluate smart mobility. The main sub-themes/subsets in the existing literature are private transport system, public transport system, innovation/ICT and sustainability. For example, all sustainability-related indicators are combined into the sustainability index (Battarra et al., 2018a). The identified indicators in Table 3 can be grouped into three themes: accessibility, sustainability and innovation (Battarra et al., 2018a; Pop and Proștean, 2019).

Diverse groups' key variables/themes and indicators assess smart transport in numerous studies. However, the categories in some studies could not represent the whole picture of smart transport systems in a city. For example, emergency transport is often neglected in smart transport research. Many indicators/variables are related to the sharing economy and use bike-sharing and car-sharing as important innovation indicators. Other advanced innovation technologies, such as MaaS, are not included in the existing index. Regarding empirical studies, the most studied cases are Italian and Spanish cities. UK cities have not yet been thoroughly assessed in terms of smart transport. A topology of smart transport development in UK cities can contribute to the existing literature.

Building a smart transport evaluation framework for English metropolitan areas

This study builds on the review above and follows a typical indicator selection process (Sdoukopoulos et al., 2019). We first select the most used indicators from the literature and supply existing indicators with potential new indicators. We finalise individual indicators by checking quality selection criteria, data availability and duplication. To illustrate the latest trends in smart transport, we added five new indicators to the final indicator list. After building the individual indicator list for evaluating the specific aspect of smart transport technologies, methods and infrastructures, the indices are constructed by scaling up indicators from different subsets. Six indices (i.e., private transport index, public transport index, emergency transport index, accessibility index, sustainability index and innovation index) are aggregated. Finally, a composite index is calculated to quantify the overall development of smart transport. A comprehensive and detailed picture of smart transport in each case can be demonstrated using the individual indicators. The key elements in smart transport (e.g., the overview of the public transport system) can be shown by aggregated indices (e.g., public transport index). We can further compare the general situations in various cases using the composite index. The individual indicators, aggregated indices and composite index make up the new evaluation framework for smart transport.

Building a disaggregated indicator list

The selection of smart transport indicators in this study follows a four-step procedure. Firstly, the systematic review in the last section allows us to identify the most common indicators. The most used indicators (in Table 3) are included in our thorough list of potential indicators. Some of the indicators can be illustrated by several detailed indicators. For example, public transport supply/service can be represented by bus/rail/metro length/network, depending on the data availability in each study.

The second step constructs the potential new indicators to supplement the current indicators. Policy documents, reports and articles have also discussed other new themes that have not been included in the current indicators. Private-hire cars, shared travel, Mobility-as-a-Service (MaaS, i.e., one-stop online intermodal journey planner), intersections between physical and digital infrastructures, data and connectivity, electrification, decarbonisation, automation, and new business models are trending themes in governmental documents (GO-Science, 2019). MaaS, Internet of Things (IoT) and open data have been mentioned in the future mobility chapters of many transport interventions. Academic studies from recent years also discuss IoT (Mohanty et al., 2016; Mohammadian and Rezaie, 2020; Crainic et al., 2019; Shaheen et al., 2019), open data and data-driven products (Tomaszewska and Florea (2018); Kumar et al. (2017, 2018); Xu and McArdle (2018); Shaheen et al. (2019)), MaaS (Cruz et al., 2018; Anthony et al., 2020; Li, 2019; Finger and Audouin, 2019), self-driving or driverless cars (Šurdonja et al., 2020; Toh et al., 2020) and emergency service tracking (Šurdonja et al., 2020).

Among these new themes, MaaS, IoT, self-driving vehicles and open data are not included in the existing indicator set. New innovation indicators on these four themes can supplement the current set. Additionally, indicators on emergency transport systems are rare in the existing literature. Indicators for normal ambulance performance and performance in a time of pandemic as well as smart ambulance are added to illustrate the accessibility and innovation of a smart emergency transport system.

Thirdly, we check the quality selection criteria and data availability for all potential indicators to finalise indicators. The criteria for selecting indicators contains measurability, ease of availability, interpretability and the isolability of transport impact (Castillo and Pitfield, 2010). Regarding data, the sources in this study include the National Travel Survey 2017 (NTS) (Department for Transport, 2020), road accidents and safety statistics, vehicle statistics, bus statistics, rail statistics from the Department for Transport[5] (DfT), Highways England[6], Centre for Connected and Autonomous Vehicles[7] (CCAV), as well as statistics from the Department for Business, Energy and Industrial Strategy[8] (BEIS), Office for National Statistics[9] (ONS), National Health Service[10] (NHS), and Public Health England[11] (PHE). The main dataset in this study is NTS 2017. Thus, we mainly use data from 2017 to 2020 to illustrate the latest smart transport situations in English metropolitan areas.

Simultaneously with the previous work, we also review webpages of city authorities, services providers, related companies, consultant reports and news agencies, using Google Search Engine to collect information. We search for keywords and the city names (Debnath et al., 2014; Pindarwati and Wijayanto, 2015). Eleven indicators used the data from webpage mining with Google. Apart from restricted schemes

[5] https://www.gov.uk/government/organisations/department-for-transport/about/statistics.

[6] https://www.gov.uk/transport/smart-motorways#research_and_statistics.

[7] https://www.gov.uk/government/organisations/centre-for-connected-and-autonomous-vehicles.

[8] https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy/about/statistics

[9] https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare

[10] https://digital.nhs.uk/data-and-information/data-insights-and-statistics

[11] https://www.gov.uk/guidance/phe-data-and-analysis-tools

and trial CAV projects, other indicators are on/off to reduce the potential error of miscounting. For new indicators, we have data only on MaaS and Open data API in public transport, and ambulance disposition rate, ambulance disposition rate changes due to the pandemic, and connected ambulance in emergency transport. Thus, the five new indicators are added to supply the existing toolkit.

Fourthly, as the indicators are equally weighted in aggregating into indices, we also check the duplication of similar indicators and delete similar indicators to avoid over-representing one aspect. For example, the mobility difficulties (e.g., personal disability and poor connections) in private transport can be illustrated by either the number of blue badges (disabled parking permits) or the percentage of users who have mobility difficulties in cars. We choose the latter one as it contains the most comprehensive information.

Based on the four-step procedure, the final evaluation framework contains 38 existing indicators and five new indicators (broad in Tables 4–6, column 2). We choose three subsets to show different transport sub-systems in a city, namely private transport (including walking and cycling), public transport and emergency transport systems. In each subsystem, we further classify the indicators into three themes: accessibility, sustainability and innovation. Accessibility concerns "the ability of places to be reached", relevant resources (e.g., car for private transport and bus for public transport) and affordable cost for local people (Battarra et al., 2018a). Sustainability considers environmental aspects such as energy consumption, and social-economic aspects include issues such as road safety. Innovation deals with new technologies and new business models used in the transport system.

Three types of indicators are listed: 1) percentage indicators (N%) such as private vehicle rate (PV_A2_vehiclerate); 2) number indicators (N) such as the number of urban access regulation schemes (PV_S1_restrictedschemes); and 3) on and off indicators (1/0) such as whether a metropolitan area has CAV hard infrastructure (PV_I9_CAVhardinf). Ideally, percentage and number indicators should be used to show detailed information in each field. When detailed information is not available or accessible, we use the on and off indicators. Binary indicators are mostly about innovation features, showing the presence or absence of each innovative product or service. The data sources we accessed cannot provide more accurate information (e.g., the actual number/percentage) in these features, so we use the on and off value. The types of indicators are shown in the unit column.

The indicators can be either positive or negative. Positive indicators mean the indicators have a positive impact on the corresponding theme. For example, car access with car or vans in a household leads to greater accessibility, making PV_A3_caraccess a positive indicator. On the contrary, negative indicators are the factors that can decrease the level of each theme. For instance, the higher mean of particulate matter (PM2.5) indicates less environmental sustainability. The detailed indicators of each variable are listed below (Tables 4–6).

Synthesizing the smart transport indicators into aggregated indices

The units and results of the selected indicators in the previous section vary. To build an index by aggregating individual indicators, the result of each indicator needs to be rescaled into a common range. We applied the most commonly used method in existing studies, namely Min-Max normalisation, to rescale the results (Garau et al., 2016, Garau et al., 2015, Lopez-Carreiro and Monzon, 2018). In all positive indicators except PV_A0_traveltime and PB_A0_traveltime, a larger number indicates better performance. For other positive indicators, the best result will be rescaled to 1 and the worst to 0, using formula (1). Negative indicators will be rescaled from 0 (the worst) to 1 (the best), using formula (2). For PV_A0_traveltime and PB_A0_traveltime, less time used in travelling to the key services means better accessibility. Thus, the rescaling of two travel time indicators is special, using the formula (2).

$$\text{Positive indicators}: Xir = \frac{Xi - Min(Xi)}{Max(Xi) - Min(Xi)} \tag{1}$$

$$\text{Negative and special indicators}: Xir = \frac{Xi - Max(Xi)}{Min(Xi) - Max(Xi)} \tag{2}$$

Table 4
Selected indicators for private transport.

Themes	Indicators	Description of indicators	Unit	P/N	Data sources
Accessibility	PV_A0_traveltime	Average minimum travel time to reach the nearest key services by car, 2017	N	+	DfT
	PV_A1_roadnetwork	Road network length, Km/km2	N%	+	DfT
	PV_A2_vehiclerate	Number of private vehicles per inhabitants	N%	+	DfT
	PV_A3_caraccess	car access (with car/van)	N	+	NTS
	PV_A4_modechoice	% private modes (car and van, motorcycle, other private transport)	N%	+	NTS
	PV_A5_mobdifficulties	%Mobilities difficulties in cars	N%	–	NTS
	CW_A1_modechoice	% walking and cycling mode	N%	+	NTS
	CW_A2_footdifficulties	%Mobilities difficulties on foot	N%	–	NTS
Sustainability	PV_S1_restrictedschemes	urban access regulation schemes: low emission zones, urban road tolls, other access regulation	N	+	Google
	PV_S2_ecologicalcars	% Ultra-low emission vehicles (ULEVs) licensed in all registered vehicles, 2019	N%	+	DfT
	PV_S3_electriccharging	Publicly available electric vehicle charging devices per 100,000 inhabitants by local authority, 2019	N%	+	DfT
	PV_S4_airquality	Population-weighted annual mean of pm2.5, 2018	N	– –	UK Air
	PV_S5_roadfatalityrate	Number of road fatalities by car per 100,000 inhabitants, 2019	N%	–	PHE
	PV_S6_roadenergyconsumption	Road transport energy consumption (Tonnes of oil equivalent of diesel, petrol cars and motorcycles), 2017	N	–	BEIS
	CW_S1_roadfatalityrate	Number of road fatalities by walking and cycling per 100,000 inhabitants, 2019	N%	–	DfT
Innovation	PV_I1_carclub	Car-sharing demand, number of car club members per 1000 inhabitant	N%	+	NTS
	PV_I2_PHV	Ride-sourcing supply, licensed private hire vehicles per 1000 inhabitant	N%	+	DfT
	PV_I3_smartmotorway	% Number of operational smart motorways in total road length	N%	+	Highway England
	PV_I4_mobilealarm	SMS/mobile notification for traffic alert	1/0	+	Google
	PV_I5_VMS	Variable message sign/matrix sign/Variable Signs and Signals	1/0	+	Google
	PV_I6_realtimeforcast	Real-time traffic forecast	1/0	+	Google
	PV_I7_internetaccess	% Internet users, 2019	N%	+	ONS
	PV_I8_CAVsoftinf	CAV soft infrastructures: virtual labs	1/0	+	CCAV
	PV_I9_CAVhardinf	CAV hard infrastructures: testbeds	1/0	+	CCAV
	PV_I10_CAVproject	Number of trial CAV projects	N	+	Google
	PV_I11_ITSproject	Intelligent Transport System projects funded by DfT	1/0	+	DfT

Table 5
Selected indicators for public transport.

Variables	Indicators	Description of indicators	Unit	P/N	Data sources
Accessibility	PB_A0_traveltime	Average minimum travel time to reach the nearest key services by public transport and walking, 2017	N	+	DfT
	PB_A1_busservice	Public transport supply: Vehicle kilometres on local bus services by local authority, 2018/2019 (million)	N	+	DfT
	PB_A2_busjourney	Public transport demand: passenger journeys on local bus services 2018/19 (million)	N	+	DfT
	PB_A3_modechoice	% public mode (bus, London underground, rail, taxi, other public transport)	N%	+	NTS
	PB_A4_buscosts	Local bus fares index (at current prices) by metropolitan area status and country	N	–	DfT
	PB_A5_busdifficulties	%bus difficulties	N%	–	NTS
Sustainability	PB_S1_ecobus	ecological buses?	1/0	+	Google
	PB_S2_energyconsumption	Road transport energy consumption (Tonnes of oil equivalent of diesel, petrol cars and motorcycles), 2017	N	–	DfT
	PB_S3_roadfatalityrate	Number of road fatalities per 100,000 inhabitants, 2019	N%	–	DfT
	PB_S4_interventions	Sustainable actions/objectives in public transport in smart transport intervention?	1/0	+	Policy review
Innovation	PB_I1_CCTV	% buses used as Public Service Vehicles with CCTV by metropolitan area status and country, local bus operators only	N	+	DfT
	PB_I2_AVL	% buses used as Public Service Vehicles with automatic vehicle location (AVL) device by metropolitan area status, local bus operators only	N	+	DfT
	PB_I3_AVLrealtimeifo	% buses with an AVL to provide real-time service information to customers by metropolitan area status, local bus operators only	N	+	DfT
	PB_I4_Wifi	% buses used as Public Service Vehicles with free Wi-Fi by metropolitan area status and country, local bus operators only	N	+	DfT
	PB_I5_MaaS	Mobility as a service?	1/0	+	Google
	PB_I6_buslane	detection of unauthorised vehicles: Have a bus lane/bus only/bus gate enforcement system?	1/0	+	Google
	PB_I7_contactlessticket	% buses with live EMV readers that can accept contactless payment cards1 by metropolitan area status, local bus operators only	N%	+	DfT
	PB_I8_integratedticket	%buses with live readers that accept Oyster/ITSO Smart-cards1 by metropolitan area status, local bus operators only	N%	+	DfT
	PB_I9_openapi	Open data platform/API?	1/0	+	Google

Table 6
Selected indicators for emergency transport.

Variables	Indicator	Description of indicator	Unit	P/N	Data source
Accessibility	**ET_A1_ambulancedispositionrate**	%Number of emergency ambulance dispositions/inhabitant, in May 2019	N%	+	NHS
	ET_A2_pandemicchange_ambulancedispositionrate	% Increase in number of emergency ambulance dispositions compared to normal time, pandemic period (March 2020) and normal time (May 2019)	N%	+	NHS
Innovation	ET_I1_signals	Emergency vehicle priority signal – able to provide priority signal?	1/0	+	Google
	ET_I2_connectedambulance	Trial digital/connected/smart ambulance? Ambulance Global Digital Exemplars?	1/0	+	Google

Where:
Xir: re-scale value of X_i
Xi: initial score of the indicator
Min(*Xi*): the minimum value of the indicator
Max(*Xi*): the maximum value of the indicator

On and off indicators do not need to be recalculated. The rescaling process is done in R (Team, 2013). After rescaling, the indicators can be aggregated into indices.

Three groups of indices are constructed: 1) three synthetic indices for different transport systems, 2) three synthetic indices for different themes (i.e., Accessibility, Sustainability, and Innovation), and 3) smart transport index. Following the commonly used synthetic approach (Battarra et al., 2018a, Battarra et al., 2018b, Lopez-Carreiro and Monzon, 2018), we calculate the average value of all indicators in each theme/category (Formula 4) to construct the synthetic indices. Previous studies have weighted indicators or sub-systems to reveal the relative importance of different elements in smart transport systems (Lopez-Carreiro and Monzon, 2018; Li et al., 2019). Expert/stakeholder opinions have often been used to decide the weights. This method requires extensive time and resources to collect data (Debnath et al., 2014). Thus, we decide to use equal weight for all variables and individual indicators in this study, as most authors did (Garau et al., 2016, Garau et al., 2015, Lopez-Carreiro and Monzon, 2018, Pinna et al., 2017).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{3}$$

For the first group, private transport index (I_{PV}), public transport index (I_{PB}) and emergency transport index (I_{ET}) are calculated by the mean of indicators in each transport system. The formulas are as below:

$$IPV = \frac{\sum_{i=1}^{n} PVi}{n} \tag{4}$$

$$IPB = \frac{\sum_{i=1}^{n} PBi}{n} \tag{5}$$

$$IET = \frac{\sum_{i=1}^{n} ETi}{n} \tag{6}$$

Where:
PV: Private transport (including walking and cycling) indicators in Table 4
PB: Public transport indicators in Table 5
ET: Emergency transport indicators in Table 6

Similarly, accessibility index (I_A), sustainability index (I_S) and innovation index (I_I) are calculated in the formulas (7), (8), and (9). These three indices are the most common used aggregated indices to show the three pillars of the transport system.

Table 7
Comparison between smart transport ranking and interventions.

Cases	Smart transport ranking	Smart city category	Social-demographic status (tier)	Transport as key area in Smart city policies	Main Objectives in transport plans
Greater London	1	Leaders	1	yes	Accessibility, Sustainability, Innovation
West Midlands	2	Contenders	2	yes	Accessibility, Sustainability, Innovation
West of England	3	Leaders	3	yes	Accessibility, Sustainability, Innovation
Liverpool City Region	4	Challengers	2	yes	Accessibility, Sustainability
Great Manchester	5	Contenders	2	yes	Accessibility, Sustainability, Innovation
North East	6	–	3	no	Accessibility, Sustainability
North of Tyne	7	Contenders	3	no	–
Cambridgeshire and Peterborough	8	Contenders	3	no	Accessibility, Sustainability
West Yorkshire	9	Contenders	2	yes	Accessibility, Sustainability, Innovation
Sheffield City Region	10	Challengers	3	no	Accessibility, Sustainability
Tees Valley	11	–	3	no	Accessibility, Sustainability

$$IA = \frac{\sum_{i=1}^{n} Ai}{n} \quad (7)$$

$$IS = \frac{\sum_{i=1}^{n} Si}{n} \quad (8)$$

$$II = \frac{\sum_{i=1}^{n} Ii}{n} \quad (9)$$

Where:
Ai: Accessibility indicators listed in Tables 4–6
Si: Sustainability indicators listed in Tables 4–6
Ii: Innovation indicators listed in Tables 4–6

Composing the smart transport index

Finally, the smart transport index (I_{ST}) is defined through the formula below, which merges the three main dimensions (i.e., accessibility, sustainability and innovation) in an area. It is difficult to decide which of the three dimensions is most important in the smart transport evaluation framework. Weights for each factor may vary from case to case. For example, stakeholders in London may give a different weight to sustainability index from stakeholders from Great Manchester. Weighting variables for English cities may not be transferrable to cities in other countries. Thus, in constructing the I_{ST}, the three dimensions of accessibility, sustainability and innovation, are equally weighted in the composite index. This study uses the geometric mean (Formula 10) to show the overall transport performance (Garau et al., 2016, Garau et al., 2015, Lopez-Carreiro and Monzon, 2018, Pinna et al., 2017).

$$IST = \sqrt[3]{IA \times IS \times II} \quad (10)$$

Results of smart transport indices

This section contains the results of six aggregated indices and the composite index. In the first part, we present the results for three main transport systems, namely private transport, emergency transport and public transport in the cases. In the second part, a comparison of smart transport in terms of accessibility, sustainability and innovation is provided. The last part shows the result for the smart transport index.

Private, public and emergency transport indices

The value of the private transport index varies in each case (See Figure 1). The best private transport system is obtained in Greater London (0.710); followed by West of England (0.637) and West Midlands (0.628), Liverpool City Region (0.551), and Greater Manchester (0.545). Generally, the metropolis with greater population and better economic performance has a better private transport system. Higher GVA may lead to more resources available for local government, which can be allocated to transport infrastructures (e.g., road network) and intelligent transport projects. For example, Greater London and West Midlands have sustainable schemes such as low-emission zones and more connected and automated vehicles (CAV) test infrastructures. Additionally, people in wealthier places are more likely to have access to private cars. The top five metropolises in private transport also have higher vehicular densities. It should be noted that cycling and walking mode is counted in private transport. Relevant indicators on the non-motorised mode indicate that walking and cycling difficulties occur in many road networks in metropolises. Roughly speaking, the places with better social-demographic background have worse performance in cycling and walking.

For the public transport index, the best performance is also obtained in Greater London (0.735), followed by West Midlands (0.608), Liverpool City Region (0.603), Greater Manchester (0.593) as well as Cambridgeshire and Peterborough (0.587). These places with better economic performance provide more bus services and experience fewer bus difficulties. These metropolises have a wide range of smart technologies in their public transport system. For example, most of their buses are equipped with closed-circuit television (CCTV), automatic vehicle location (AVL) and smart ticketing systems. They all have open data platforms for developers to make use of the real-time and high-volume transport data for improving their transport software/application/service. These applications can benefit public transport users in these places. Also, the top areas have pilot projects or plans for Mobility-as-a-Service (MaaS), which is seen as a future user-centric trend in public transport. The MaaS is an integrated booking system providing intermodal journey planning with a single payment portal, which is believed to benefit public transport and active mode (GO-Science, 2019). The projects are City Mapper and London Transport Planner in Greater London, iMove in Greater Manchester, Whim in West Midlands, CAPITALS in Liverpool City Region, and the intelligent City Platform (iCP)[12] for Cambridgeshire and Peterborough (Bevis, 2018).

For the emergency transport index, North of Tyne (0.873), Tees Valley (0.873), and North East (0.873) ranked the first among all cases, followed by West Midlands (0.700). The North East Region working with North East Ambulance Service NHS Foundation Trust (including North of Tyne, Tees Valley and North East CAs) has the best performance in terms of both accessibility of ambulance service and

[12] https://www.connectingcambridgeshire.co.uk/smart-places/smart-cambridge/mobility-as-a-service/

smart technology used in ambulances. The value of emergency transport does not correspond to the social-demographic information.

Accessibility, sustainability, innovation indices

For the accessibility index, the values range from 0.297 in Sheffield City Region to 0.614 in Greater London. The most accessible metropolitan areas are Greater London (0.614), West of England (0.477), West Midlands (0.460), Liverpool City Region (0.418) and Tees Valley (0.405). Greater London has the best accessibility in its public transport and private transport (including cycling and walking) in all areas. West of England and West Midlands show particularly good accessibility in all transport systems. People can access to good private, public and non-motorised transport in Liverpool City Region. People in Tees Valley can get access to good emergency, public and private transport.

For the sustainability index, the best performances are obtained by North of Tyne (0.730), Tees Valley (0.703), and West of England (0.674). The worst area is Greater London (0.456). West of England has the most sustainable public transport system and a very sustainable private transport system, while Greater London has the most sustainable private transport system and the least sustainable public transport. North of Tyne and Tees Valley have high performance in terms of sustainability in public and private transport systems. Although all the areas have ecological buses or plan to introduce ecological buses, areas with more bus services/journeys witness more energy consumption by public transport. For private transport, London has the greatest number of schemes to manage air pollution, as well as the most ecological vehicles and electric charging devices; however, it also has the highest road energy consumption and the worst air pollution.

Values of the innovation index range from 0.313 to 0.883 in different English metropolitan areas. The most innovative areas are Greater London (0.883), West Midlands (0.768), Greater Manchester (0.673), Liverpool City Region (0.656) and West of England (0.608). Greater London has the best innovative capacities in both public and private transport systems. Smart technologies have been used in London's transport system, including CCTV, AVL devices, smart tickets, pilot MaaS and open data in public transport, as well as car-sharing services, intelligent transport system projects, CAV infrastructures and projects in private transport. West Midlands ranks second in its innovation in both private and public transport. It has free Wi-Fi, MaaS, integrated tickets, and open data in its public transport system. It aims to build smart future mobility, and it is now one of the premier CAV testbeds. 5G is also used to improve the connected transport system in West Midlands. Liverpool City Region and Greater Manchester have excellent innovative public transport, with smart devices, ticketing systems and pilot MaaS. West of England is another important testbed for CAV projects, so it also has innovative private transport.

However, the most innovative areas are not the places ranked highest in emergency transport innovation. Innovation in emergency transport includes emergency vehicle priority signals and trail connected ambulance projects. South Central Ambulance Service NHS Foundation Trust, West Midlands Ambulance Service NHS Foundation Trust and North East Ambulance Service NHS Foundation Trust are working on the digitally advanced ambulance to become Ambulance Global Digital Exemplars[13], which refers to "an internationally recognised NHS provider delivering improvements in the quality of care, through the world-class use of digital technologies and information"[14]. Thus, the most innovative places in emergency transport are North of Tyne, North East and Tees Valley.

Smart transport index

The smart transport index (I_{ST}) considers the dimensions of accessibility, sustainability and innovation in transport systems, which are three main pillars in smart transport. The index is a tool to summarise and simplify the overall smart transport developments with multidimensions in each case. Ranking the results of the I_{ST} can compare the divergent performances in smart transport in the selected cases.

The result shows that Greater London (0.628) is the smartest among the eleven metropolitan areas, with the best accessibility and innovation performance. The other top smart transport areas are West Midlands (0.591), West of England (0.580), Liverpool City Region (0.549), and Greater Manchester (0.533). The ranking is listed in Table A3 (in Appendix). As shown in the map (Fig. 2), the northern areas have worse performances than the southern cities. Generally, Greater London in the first-tier metropolis ranked the first in smart transport index. Those in the second-tier metropolises have high rankings in smart transport index. One exception is West of England, with a relatively small population, but a very high ranking in terms of its smart transport index.

Discussion

Linkages between indices, smart transport ranking and interventions

We rank the eleven English metropolitan areas by the six aggregated indices that present the main aspects in the transport system and compare the rankings of each index with the composite smart transport index. As shown in Fig. 3, the areas with highest rankings in the overall smart transport systems generally have good rankings in private and public sub-systems. The high-ranking areas usually have good accessibility and sustainability. However, good rankings in emergency transport are not seen in the top areas. These areas often have a low score in sustainability.

Considering the social-demographic status of metropolises, the sole first-tier city Greater London (GL) ranks the first in smart transport. The second-tier cities often have better scores than the third-tier areas. The two exceptions are West Yorkshire (WY) and West of England (WE). The relatively poor accessibility in WY prevents it from having a high smart transport ranking. On the contrary, WE is relatively small and thinly populated, but it has excellent accessibility and sustainability, especially in its private transport system. The social-demographic status of metropolises may be positively linked to the smart transport ranking.

Smart transport is a key component of a smart city. In the UK, the leaders in smart city development (i.e., GL and WE) also have top rankings in smart transport, and probably all other main sectors. While other smart cities each have a different innovation focus, as mentioned in Section 2.2, the ranking of smart transport in the contender group varies (see columns 1 and 2, Table 7). A smart city in the contender group may have a less-smart transport sector.

Roughly speaking, the regions that have transport as one of the key areas in their smart city focus and highlight innovative objectives in their main transport interventions (see columns 5 and 6, in Table 7) are likely to rank high in the smart transport index. This indicates that political attention is likely to be positive to the development of smart transport. Areas setting transport as a political focus rank higher than other areas in smart transport index, except WY. In the cases where innovation is not the main objective of their main transport strategies, the smart ranking tends to be low, as illustrated in North East, Sheffield City Region and Tees Valley. An exception is Liverpool City Region (LCR); innovation is not a key goal or a main chapter in the LCRCA transport plan, although this plan mentioned smart ticketing and smart motorways. LCR has several smart transport projects and a relatively good accessibility index. Another exception is WY, as explained above. Initiatives and political attention could have a positive impact on the development of smart transport in a city.

[13] https://www.england.nhs.uk/digitaltechnology/connecteddigitalsystems/exemplars/ambulance-global-digital-exemplars/.

[14] https://www.england.nhs.uk/digitaltechnology/connecteddigitalsystems/exemplars/.

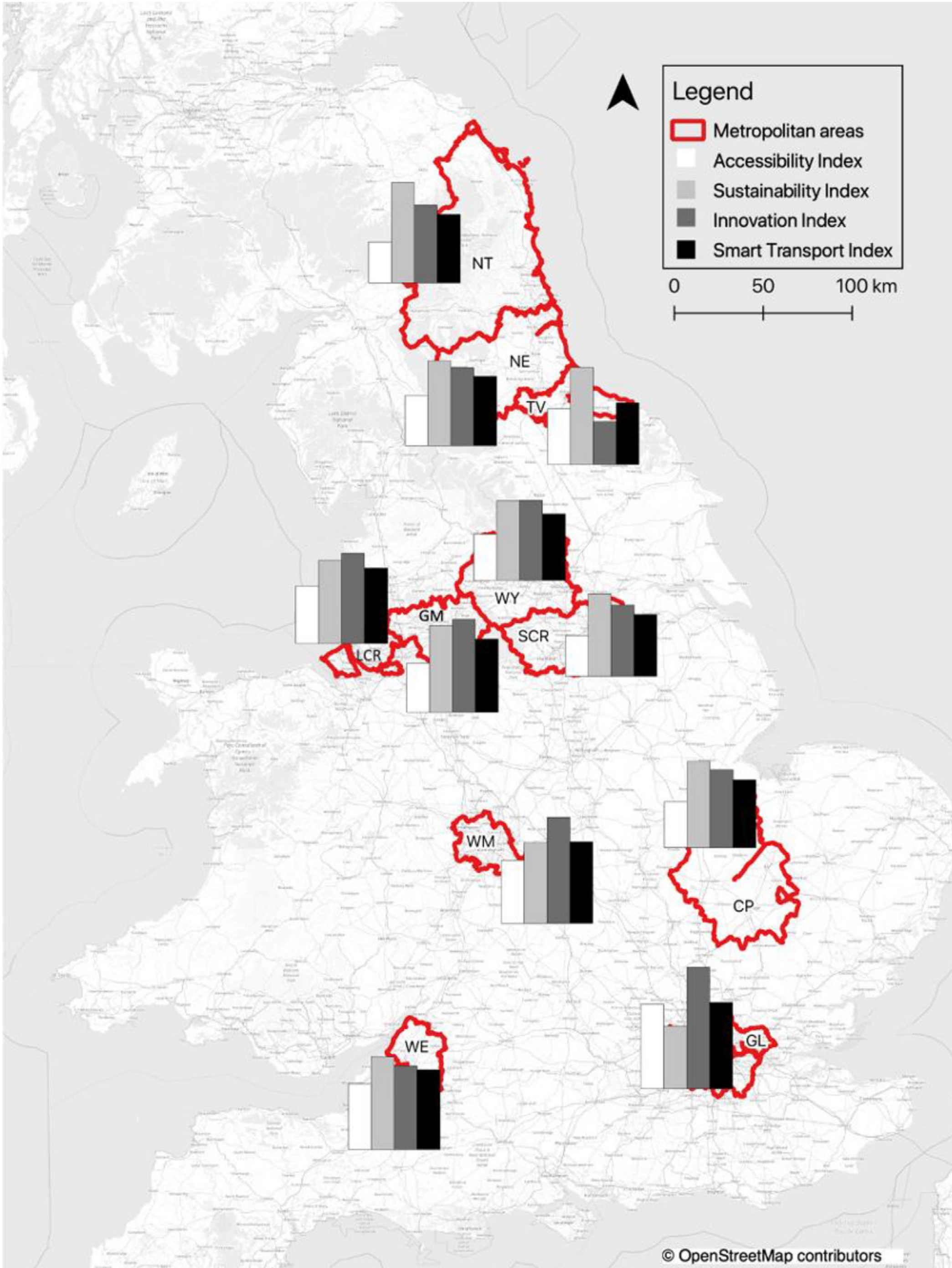

Fig. 2. Smart transport indices in English metropolitan areas.

Adaptive transport planning for emerging technologies

The rapid technological innovation and fast adoption of innovative technologies in the transport sector are challenges for constructing a smart transport index. This requires new variables and dimensions to be added in time and prepares transport planning in response to the uncertainty in the transport system. Uncertainty has been a concern for policymakers and urban and transport planners for a long time. Based on complexity theory and data science, urban researchers suggest that adaptive planning can help manage the uncertainties and emerging innovation in cities (Rauws, 2017, Rauws and De Roo, 2016; Chen and Silva, forthcoming). Adaptive planning considers various future scenarios with different triggers and pathways. Monitoring potential technological changes, reassessing the current plans when facing new triggers, preparing the trigger responses, and conducting various transport scenario planning are examples of the adaptive approaches in transport planning (Walker et al., 2019, Lyons and Davidson, 2016). The adaptive transport planning approaches can help increase the flexibility in planning processes, encouraging planners to think through "what-if" scenarios, exploring alternative developing situations in facing emerging technologies, preparing for different pathways, emphasizing the planning processes rather than optimal results, and supporting actors' cooperation (Chen and Silva, forthcoming; Lyons and Davidson, 2016).

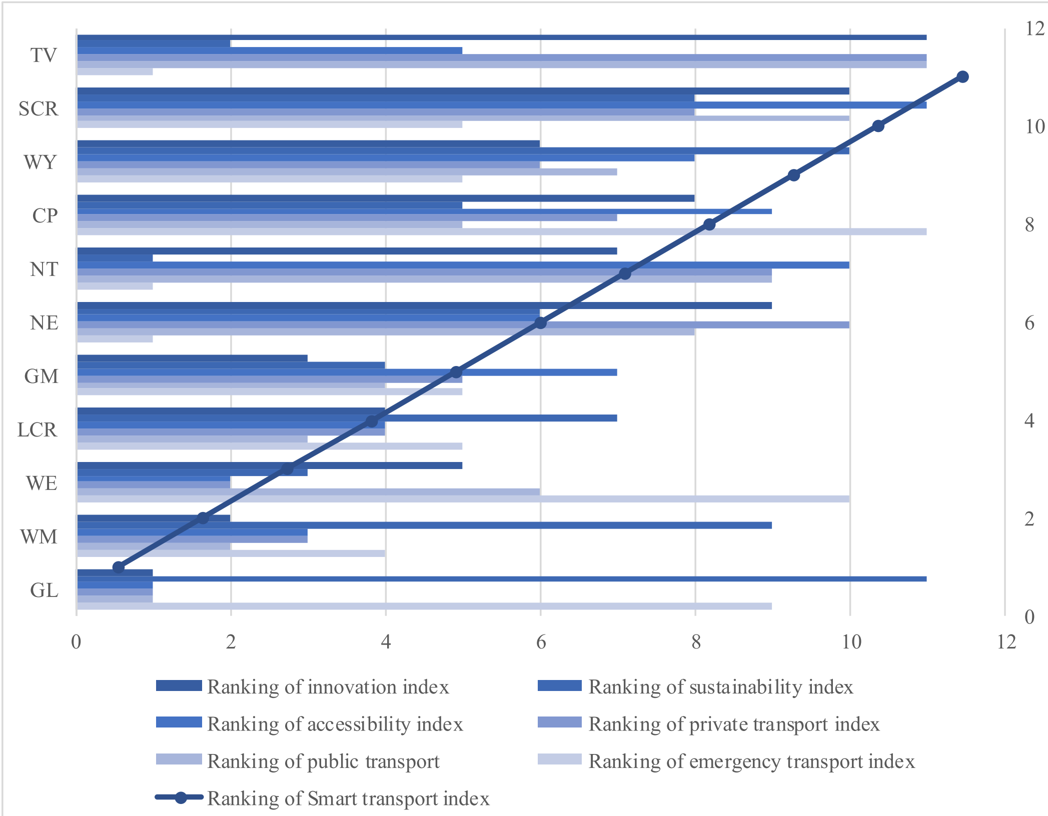

Fig. 3. Comparison of index ranking.

As shown in Section 2, emerging technologies such as CAV are highlighted in almost all transport plans in the eleven cases and all transport strategies stated that preparing for future mobility is needed. Nevertheless, none of the transport plans has a detailed strategy or a certain plan to deal with emerging technologies because there could be many potential future scenarios. Thus, facing highly uncertain future mobility, transport planning needs to increase its flexibility and resilience. The adaptive planning approaches are likely to benefit this kind of planning.

Conclusion

Smart transport is widely considered a key sector within smart cities as it can impact society, environment and the economy. The uncertainty of future mobility and ambitious on-going visions of smart transport interventions require universally accepted methodological tools. Tools such as a robust evaluation framework can unveil the full picture of the different dimensions in smart transport development. In this context, we propose a comprehensive framework for evaluating smart transport in English metropolises, based on the most used indicators, current trends and data availability. Our study contributes to the existing literature and current toolkits on smart transport analysis by identifying the most used indicators, constructing a new evaluation framework with multidimensions included, and applying it in new empirical cases.

The evaluation framework in this study contains 44 existing commonly used indicators and five new indicators. The new indicators are MaaS and Open data API in public transport, as well as ambulance disposition rate, ambulance disposition rate changes due to the pandemic, and connected ambulance in emergency transport. The new indicators can gauge smart transport products, service and quality. The 49 individual indicators are aggregated into three groups of indices.

The first group consists of private, public and emergency transport sub-systems. Most of the previous studies neglect emergency transport, mainly because of data limitation. As it is an important transport sub-system in cities, especially in facing the recent global health crisis, we manage to include several indicators to illustrate its quality and smartness. The second group contains accessibility, sustainability and innovation indices. The innovation index includes three new indicators. The new innovation index contains more recent technological innovation such as CAV, MaaS, and IoT, which has been proposed and implemented in the past two to three years (GO-Science, 2019). The innovation index can best represent the technologically advanced aspects and illustrate future potential. The last group is the composite index of the smart transport index. The three pillars of smart transport - namely accessibility, sustainability and innovation - are aggregated into one final index. The smart transport index can reveal the overall development of the smart transport sector in each city.

This study also contributes to the existing understanding of smart transport in the UK in terms of overall development, sub-systems, and interventions. The findings show that Greater London has the best performance in many sub-systems and aspects, followed by West Midlands and West of England, while the other areas have strengths in various aspects. Zooming into different sub-systems, Greater London, West of England and West Midlands score best in private transport. The best public transport performance can be found in Greater London, West Midlands, and Liverpool City Region. Emergency transport results are slightly different from the other systems. North of Tyne, North East, and Tees Valley have the highest rankings. As for different aspects of smart transport, the most accessible areas are Greater London, West of England, and West Midlands. North of Tyne, Tees Valley and West of England are the most sustainable areas. The most innovative areas are Greater London, West Midlands and Greater Manchester.

All English metropolitan areas have adopted smart city interventions, with special emphasis on the economy, business, health, transport and other sectors. Transport is one of the key systems that a smart city can work on. Metropolises with a focus on smart transport tend to score higher in the smart transport index. Political attention could be positive for smart transport development. The results or implementation of the policies may vary, but the places with more political attention to smart transport have a better performance in terms of accessibility, sustainability and innovation. Accessibility and sustainability are common objectives in all transport plans of English metropolitan areas. All transport strategies mentioned emerging technology and stated that there is a need to prepare for future mobility. However, not all authorities listed innovation as the main goal in their transport plans. Although all metropolises realised the importance of preparing for smarter future mobility, most of the transport plans only discuss the possibilities without detailed strategies. This is because future mobility is highly uncertain in terms of emergent technology. It requires the related plans to be shifted from static to adaptive.

These findings provide useful insights for sub-regional authorities and their transport authorities. Firstly, the results reveal the overall smart transport development in each metropolis and the performances in the sub-systems (i.e., private, public, and emergency) and main aspects (i.e., accessibility, sustainability, and innovation). Each metropolis has its advantages and weaknesses in specific areas; thus, priority areas to be improved can be easily identified. Secondly, potential factors that can influence the development of smart transport include social-demographic background, geographic locations, and interventions. Against the background of the North-South divide and disparities among metropolitan areas, southern and wealthier areas often have the most resources for developing their smart cities, including the innovation in the transport sector. Balancing the smart transport development also requires a more even urban development, which is also one reason to build combined authorities outside London. Lastly, as for the interventions in each authority, adaptive transport planning that considers potential smart transport scenarios in different timeframes is needed in facing the uncertainty in smart transport development. Also, the authorities could actively invent the future of smart mobility to support smart city development.

Our proposed framework with multidimensional indicators is used to evaluate the English metropolitan areas in this study. It can also be applied in other spatial tiers in the UK, including local authority district level, regional level and even country level, as well as in other countries. The methodology in this research can easily be duplicated in other spatial levels and places. Using the evaluation framework in this study, researchers or practitioners can compare the smart transport developments holistically or in detailed dimensions, main subsystems and key aspects. Adding more cities and areas for comparison using the proposed framework is a further direction.

Smart transport is developing dynamically with emerging innovations. This study considers some innovations and includes the emergency transport system in our evaluation framework. As time goes by, the proposed framework may be extended by adding new indicators to match future mobility trends and needs. This is also an area for further research.

The research is not without limitations. Data availability is a limitation in selecting indicators and constructing the index. Ideally, all variables should be in the same period, such as 2019. Because of the data limitation, we expand the time period to three years (2017–2020) in this study. The index shows the result for the most recent three years. Additionally, individual indicators such as bike-sharing are not included in the index because the data are not available or accessible on the metropolitan scale. Further studies can incorporate new datasets on topics such as IoT, 5G and self-driving when new data on these innovations become available. Additionally, the indicators and variables are equal-weighted and have not been validated. Further development of the evaluation framework might be a validated and weighted model/index. Through soliciting relevant stakeholders' opinion, a weight to each variable/indicator can be introduced and pilot results can be validated and corrected. Another limitation of this study is that we focus mainly on smart technologies in smart cities and smart governance. Further research could broaden the criteria of smart city intervention and provide a more comprehensive review of smart city/transport interventions in the English metropolises. With a deeper understanding of the smart city and smart transport, we can more effectively link indices with interventions.

CRediT authorship contribution statement

Yiqiao Chen: Conceptualization, Data curation, Methodology, Software, Visualisation, Writing - original draft, Writing - review & editing. **Elisabete A. Silva:** Conceptualization, Data curation, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing.

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Appendix A

Table A1
Population, area, density and GVA of the metropolitan cities.

Combined authorities	Areas (km2)	Population[1]	Density	Total GVA[2]
Greater London	1569	8,908,081	5678	431,164
West Midlands	902	2,916,458	3235	66,667
Greater Manchester	1276	2,812,569	2204	66,413
West Yorkshire	2029	2,320,214	1143	50766[3]
Liverpool City Region	726	1,551,497	2138	32,030
Sheffield City Region	1552	1,402,918	904	25,991
North of Tyne	5222	1,157,170	222	18,863
West of England	958	938,155	980	29,295
Cambridgeshire and Peterborough	3396	852,523	251	24,463
North East	2576	816,000	317	37871[3]
Tees Valley	795	674,284	848	13,122

Data source: ONS
1. Population estimates are sourced from population estimates for UK, 2018.
2. GVA(B) in current prices - a balanced measure of regional GVA, 2017.
3. GVA(B) in current prices - a balanced measure of regional GVA, 2016.

Table A2
Highly cited literature on smart transport (sample reviewed articles).

Authors	Annual citation	Case study	Index/synthetic indicators	Variables/themes	Indicators	Normalization/ Standardization	Weighting
Debnath et al. (2014)	10.86	26 cities worldwide	smartness index (SI)	Private transport Public transport Emergency transport	(Private) Detection for enforcement (Toll collection, speed, red-light, occupancy), Operation1: Automated and coordinated Traffic signal control, Operation2: Automated Speed limit control, Operation3: Automated Expressway entry control, Express operation: automated parking, Transaction: paying tolls/parking charges/enforcement fines, User – Infrastructure communication: Parking information sharing, Traffic flow prediction (Public) Detection en-route, Detection for enforcement, Operation1: Transit signal priority, Operation2: Human-less transit operation, Express operation: faster transit service, Transaction: Intermodal and electronic fare collection , Vehicle – User communication1: Passenger information management, Vehicle – User communication2: Para transit management (Emergency) Operation: Emergency vehicle priority signal, Emergency Vehicle (operator) – User (driver) communication	Extent - NA, TP, PC, FC	equal
Garau et al. (2016) Garau et al. (2015)	7.4 2.5	Cagliari (Italian city) 17 Italian cities	Smart Mobility Index = (IPT*ICL *IBS *ICS *IPMSS *IPTSS)(1/6)	Public transport Cycle lanes Bike sharing Car sharing Private mobility support system Public transport support system	IBND: Bus network density, IDPT: Demand for public transport, ITLC: Traffic lights centralized ICLD: Cycle lanes density, ICLI: Cycle lanes for ten thousand inhabitants IBSD: Bicycle station density, IBPI: Bicycle per thousand inhabitants ICI: Car for ten thousand inhabitants, ISI Station for ten thousand inhabitants IVMS: Variable message sign, ISTA: SMS service for traffic alerts, IEPPS Electronic payment park systems, IAMD: Applications for mobile devices IEBSS: Electronic bus stop signs, IETPS: Electronic ticket payment system, IRSWT: Information on routes, schedules and waiting times, ITPC: Travel planner for the route calculation, ITTO: Travel tickets online	rescaling	equal
Pinna et al. (2017)	5	22 Italian cities	Smart Mobility Index1 = (Public Transport * Cycle Lanes * Bike Sharing * Car Sharing)(1/4) Smart Mobility Index2 = (Public Transport * Cycle Lanes * Bike Sharing * Car Sharing * Stalls for Interchange Parking * Electric Cars)(1/6)	Public transport Cycle lanes Bike sharing Car sharing Park stalls Electric vehicles	IBND: Bus network density IDPT: Demand for public transport ICLD: Cycle lanes density ICLI: Cycle lanes for ten thousand inhabitants IBSD: Bicycle station density IBPI: Bicycle per thousand inhabitants ICI: Car for ten thousand inhabitants ISI: Station for ten thousand inhabitants	Rescaling	Equal

(continued on next page)

Table A2 (*continued*)

Authors	Annual citation	Case study	Index/synthetic indicators	Variables/themes	Indicators	Normalization/ Standardization	Weighting
Lopez-Carreiro and Monzon (2018)	5	6 Spanish cities	Smart Mobility Index = [(Isus)2 +(Iinn)2](1/2)	Innovation Sustainability transport (social, environment, economic)	XS1: Accessibility for groups with impaired mobility, XS2: Public transport (PT) subsidies, XS3: Traffic fatalities per capita, XS4: Private vs. Public transport (PT) modes XE1: Air quality index, XE2: Motorisation rate 5, XE3: Density of cycle paths, XE4: Land consumption for transport infrastructure XC1: Time spent travelling per capita, XC2: Coverage ratio of public transport (PT), XC3: Ratio between cost of transport for user and GDP per capita, XC4: Annual expenditure on public transport investment per resident XT1: Operating Assistance Systems (OAS) coverage, XT2: Real-time information system, XT3: Electronic ticket payment system, XT4: Alternative fuels in public transport (PT)	rescaling	equal weight for indicators, unequal weight for sustainable index (from previous global sustainable study)
Lerner et al. (2011)	4	66 cities worldwide	Urban mobility index = mobility maturity + mobility performance	Mobility maturity, mobility performance	(Maturity) mode share, mobility vision, car sharing, bike sharing, smart cards, (Performance) facilities, CO2 emissions, vehicles, travel speed, satisfaction, mean travel time to work	Rescaling & extent	equal
Battarra et al. (2018a)	2.67	11 Italian metropolitan cities	Accessibility IA= (A1 + A2 + .. + An)/n, Sustainability IS=(S1 + S2 +…Sn)/n	Accessibility, Sustainability, ICT	A1: Public transport demand, A2: Public transport supply, A3: Public transport lanes, A4: Bus stop density, A5: Rail network, A6: Rail network stops, A7: Toll parking S1: Ecological buses (electric, natural gas, LPG), S2: Pedestrian zones, S3: Restricted traffic zones, S4: Cycle lanes , S5: Ecological cars (electric, natural-gas), S6: Car sharing demand, S7: Car sharing supply, S8: Bike sharing supply, S9: Bike sharing density ICT1: Road traffic signal systems, ICT2: Variable message sign, ICT3: SMS for traffic alerts, ICT4: Electronic parking payment systems, ICT5: Applications for mobile devices, ICT6: SMS for public transport information, ICT7: Electronic bus stop signs, ICT8: Electronic travel tickets, ICT9: Electronic travel ticket by mobile devices, ICT10: Information on routes, schedules, times, ICT11: LPT travel planner, ICT12: Travel tickets online	z-score standardisation	equal
Balducci and Ferrara (2018)	1.67	116 Italian cities	Principle components that contain mobility indicators	ICT, Eco-social innovation (Smart Mobility), Governance	Bike-sharing, Car-sharing, Park & Ride and pedestrian zones, Intelligent Traffic lights	rescaling	PCA
Li et al. (2019)	2	35 Chinese cities	Principle components that contain mobility indicators	Mobility sharing Multimodal access Integrated ICT system	Passengers in a vehicle, public transport vehicles, modal split of passenger transport, electronic service system	rescaling	PCA-BP neural network model

Table A3
Smart transport results for metropolitan areas.

Areas	Accessibility index (I_A)	Sustainability index (I_S)	Innovation index (I_I)	Smart transport Index (I_{ST})	Ranking
Greater London	0.614	0.456	0.883	0.628	1
West Midlands	0.460	0.585	0.768	0.591	2
West of England	0.477	0.674	0.608	0.580	3
Liverpool City Region	0.418	0.605	0.656	0.549	4
Great Manchester	0.357	0.629	0.673	0.533	5
North East	0.366	0.617	0.565	0.504	6
North of Tyne	0.299	0.730	0.567	0.498	7
Cambridgeshire and Peterborough	0.335	0.627	0.566	0.492	8
West Yorkshire	0.338	0.581	0.583	0.486	9
Sheffield City Region	0.297	0.599	0.517	0.451	10
Tees Valley	0.405	0.703	0.313	0.447	11

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