Realizing a more Coherent Quantitative Urban Science

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The candidate confirms that the work submitted is his own, except where work has formed part of jointly-authored academic publications has been included. The contribution of the candidate to this work has been explicitly indicated. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

Urban areas are centres of gravity for economic, social, political and cultural life in the 21st century. Consequentially, the processes driven by our living and working in cities drive the environmental and sustainability challenges of our time. In this PhD I explore a field of research dedicated to understanding the processes and patterns unique to urban environments through the methods and epistemologies of the natural sciences. Though more than a century in the making, efforts to advance a quantitative urbanism, sometimes referred to as a 'Science of Cities', has rapidly developed over the last two decades through the introduction of new datasets, new methodological approaches and more advanced computational power.

To understand the contribution of this field to urban knowledge and practice in the context of the climate emergency and a wider set of urban environmental challenges, I apply a reflexive approach that applies the methods and epistemologies that characterise contemporary urban environmental quantitative literature. To consider the value of larger and more available urban data, I develop a case study that uses Google Maps data to assess transport interventions in a rapidly growing city in India. To interrogate the way new methodologies and empirical approaches can embed political and normative positions, I explore the effect of data on scaling on climate action priorities in the UK. Finally, to explore the extent to which normative decisions can drive the results of empirical analyses I explore the co-benefits of climate action in urban regions of the UK.

The empirical chapters of this thesis reveal fundamental challenges facing quantitative urban environmental analysis. The first chapter demonstrates how data collection and processing can systematically exclude certain urban realities and experiences. The second shows how methodological choices shape our understanding of policy priorities and their distributional implications. The third reveals how embedded normative assumptions influence the way we value and understand urban interventions, even within seemingly objective analytical frameworks.

Collectively, these chapters highlight the need for a more epistemically diverse quantitative urbanism to contribute meaningfully to urban environmental challenges. The way we achieve a more interdisciplinary urbanism is as important, I argue, as the realisation of a quantitative urbanism characterised by a greater diversity of methods, methodological approaches, and epistemological underpinings. I conclude by proposing an approach to advancing interdisciplinary environmental urbanism based on three principles: contextual sensitivity, active and engaged transparency, and the cultivation of productive epistemological conflicts.

Table of contents

Table of Figures

Table of Tables

1 Introduction: Cities, Sustainability and the Emergence of an Urban Science

Knowledge and practice from the natural sciences have informed living and working in cities for as long as cities have existed. Systems of water management in the Indus Valley (Jansen, 1985) and the roads and public squares in Xianyang (Zhang & Wang, 2019) are just two examples of advances in mathematics and engineering sciences applied to the urban[1] that are now centuries old.

A defined academic discipline that brings together the methodological and epistemological approaches of natural science disciplines to urban research, however, has been a project of the 20th century. A turn towards urban research from biologists, for example, has been traced to academics at the University of Chicago in the 1920s (Wu, 2014). Mathematicians, physicists and statisticians increasingly developed an urban focus in the decades following WWII (Alberti, 2017; Hacking 1982). Quantitative geography emerged in the 1950s and 1960s (Batty, 2020) and subfields of economics focusing on urban areas were developed in the 1990s (Krugman 1996).

Over the last 20 years these literatures have collectively been defined by their application of empirical and positivist approaches to urban questions, have been referred to as a 'new urban science' and a 'science of cities' (Bai et al., 2017; Batty, 2021; Bettencourt & Zünd, 2020; Creutzig, 2015; Hsu et al., 2020). New and bigger datasets, improved quality of urban data and the development of new methodologies have helped this field to grow exponentially (Batty, 2020; Creutzig et al., 2019; Sethi & Creutzig, 2023; Sudmant et al., 2022). A particular focus of recent urban science of cities scholarship has been the role the field can play informing the transition to sustainable cities. Creutzig et al (2019), for example, highlight the importance of urban science for responding to the Climate Emergency while Acuto et al (2018) and Purvis (2021) are among the authors who argue that the project of a science of cities is foundational for the transition to a sustainable society.

In this thesis I make the case that the realisation of a coherent science of cities depends on the development of a more epistemically diverse field of research. To establish the foundations for this case, Chapter 1 starts by providing a historical perspective on the development of a empirical urbanism from key disciplines that have contributed to the field (1.2). In 1.3 I describe the methodological and epistemological characteristics of the contemporary empirical urban field. In 1.4 I put forward some of the key challenges facing empirical research as it is applied to urban questions. In 1.5 I put forward some of the key challenges facing positivist research as it is applied to urban questions. In 1.6 I present the research rationale. In 1.7 I present my aims and objectives. In 1.8 I present the design and methods and this thesis, and in 1.9 I present the structure of the thesis.

1.1 Historical Context and Key Sub-Disciplinary Perspectives

The "discovery" of cities by a broad array of academic disciplines and the periodic invention and reinvention of an urban science have been recurring themes throughout the 20th century. In the following I provide a brief background on some of the fields that have contributed most significantly to the development of a contemporary science of cities.

1.1.1 Quantitative Urban Geography

With the development of more advanced computer modelling techniques, practitioners from fields such as physics, mathematics, economics and ecology developed an interest in the urban in the years after WWII (Alberti, 2017). The new sets of empirical approaches and what they revealed about urban areas shifted the focus of disciplines that traditionally had not focused on cities. At the same time, disciplines that had long focused on the city, including geography, evolved as authors embraced new empirical approaches and new theoretical framings. For example, from economics, spatial geographers have drawn on theory that informs how competition and agglomeration lead to common patterns between and within urban spaces (Fujita et al., 1999).

[1] In this thesis 'cities', 'urban areas' and 'the urban' are used synonymously.

Michael Batty, a longstanding leading voice in this field, describes three foundations that have emerged as the field of spatial geography has matured over recent decades and come to embrace a Science of Cities. First, urban spatial geographers emphasise the necessity of abstracting from the observable aspects of the city that can be seen and felt, and from any notion of intrinsic attributes of people, objects or places. “What you see [in cities] is not what you get” (Batty 2020 p2). In this way urban spatial geographers emphasise the need for a relational understanding of the city that is conceptually based on an understanding that urban attributes emerge from the relationships between people, objects and physical space. Formally, this means that understandings of the city are based in the development of networks.

Second, the networks that can be developed to represent the city reveal intrinsic order. This order, in the shape of networks, their size and their number, enable relational meaning to emerge and understanding of the properties of urban spaces. Power laws capture the way processes scale as cities grow and reveal that the basic elements that make-up the city are hierarchically ordered (Batty & Longley, 1994). The development of networks thus leads in one direction to complex but highly ordered systems such as fractals, and at the same time towards an understanding of the ‘elementary units’ (agents, cells, actors), that makeup the city (Batty, 2016).

Finally, the relationships developed are predictive in nature. The networks and their properties are thus not of ‘an urban’, but of ‘the urban’ – they are relationships that speak, conditional on the context of the data that underpins them – to a wider set of urban spaces. This includes both places that have not been observed, and to the future and past of places that have been observed.

1.1.2 A Statistical Physics of the Urban

With origins in Jane Jacob’s conceptualisation of the city as a problem of ‘organised complexity’ (Jacobs 1961), and architect and designer Christopher Alexander’s critical analysis of the social and structural nature of the urban (Alexander & Mehaffy, 2015), a set of authors with backgrounds in the mathematical sciences and physics have approached the city as a challenge of interacting social and physical elements. Core to the approach of these authors is a form of complex interaction Bettencourt refers to as ‘metadynamics’: Where the interaction of systems which are themselves complex leads to meta-complexity that requires new tools and methods of analysis (L. M. A. Bettencourt, 2021).

Pointing to work in sociology, economics and anthropology as providing foundations for a statistical physics of the urban, Bettencourt outline five general properties of cities that inform a statistical physics of the urban (Bettencourt, 2021). First, cities are characterised by heterogeneity. This heterogeneity can be seen in the variety of the businesses, cultures, backgrounds, and socio-economic status of urban inhabitants, and diversity typically increase with city size. Second, urban contexts are characterised by interconnectivity. This interconnectivity exists within and between the people, objects and places that make up a city such that it can be challenging to understand a network of any of these things without the considering each of the other networks simultaneously.

Third, scaling, captures the empirical consistencies within and between cities that arise as elements of cities (typically their population) increases. The search for and identification of scaling laws (discussed below), forms the basis of a large body of statistical physics of the urban analysis. Fourth, circular causality captures the feedbacks, dependencies and contingencies between the processes taking place in cities that obscure clear lines of causality. Finally, a notion of ‘evolution’ and continual change captures the way cities’ dynamism is a fundamental feature of their nature.

A number of what are variously referred to as “coarse grained regularities”, “universals” and “laws” have been identified by key science of cities authors (Bettencourt et al., 2007; L. Bettencourt & West, 2010; Louf & Barthelemy, 2015). Bettencourt and Zünd (2020), for example, develop a framework based on demography to show how migration between cities, together with birth and death rates, determine city size distributions. In so doing, Bettencourt and Zünd (2020) provide a theoretical basis for Zipf’s Law and a wider set of empirical consistencies across urban areas. Along similar lines, Verbavatz and Barthelemy (2019) develop a stochastic equation to show that rare but large migratory shocks dominate city growth, suggesting the need for urban science to account for significant, unplanned events.

While having strong similarities in approaches to urban questions and methodologies applied, urban spatial geographers and authors who contribute to a statistical physicists of the city can be differentiated along two dimensions. First, while empirically focused urban geographers (such as Michael Batty), focus their work towards "actionable insights" (Higham et al., n.d., p. 5) statistical physicists of the urban focus on the defining the laws and rules that underpin urban processes. A practical versus fundamental divide can be found in authorship. Telling, in this respect, is the synonymous use of the terms 'urban informatics' and 'urban science' in some work by urban geographers (Batty, 2021). This is not to suggest, however, that statistical physicists who work on cities are purely theoretical in their focus. The work from Bettencourt and Zünd (2020) mentioned previously, for example, highlights how strong and lasting deviations from the expected distribution of city sizes can reveal economic transitions and changes and changes in migration patterns.

Second, authors who write on the statistical physics of the city generally describe their work as contributing towards a single overarching science. Lobo (2020, p. 10), for example, describes a science of cities "[capturing] fundamental processes that lie at the core of all human spatial agglomerations, whether these are past or present, agrarian or industrial, in developed economies or developing countries… In the same way that evolution applies to the fossil record as well as living populations." Batty, by contrast, refers to "many sciences of cities" and notes many aspects of cities, including those that are political and social, that his science does not consider (2020, p. 16). Statistical geographers are thus more likely to see other approaches to the city augmenting their own and contributing in a complementary fashion to a wider understanding of the urban. Authors who work on the statistical physics of the urban, by contrast, are more likely to see other authorship contributing to the derivations within their models.

1.1.3 Urban ecology

Cities have long been compared to biological, and indeed human, systems. Plato's Republic makes a detailed comparison of the parts of a city and the human soul, designers in the 17th and 18th centuries regularly conceived of urban infrastructure as 'arteries' and veins', and urban parks as 'lungs', and in the 20th century key urban theorists including Geddes, Mumford, Park, and Jacobs drew on Darwin's theory of evolution to describe cities' growth and change (2019).

Historically, however, the place for natural science was almost by definition seen to be outside of the city. Environmental movements of the 19th and early 20th centuries, built around the conservation and preservation schools of environmentalism, defined 'nature' by the degree of human influence (White, 1992).

Contemporary perspectives on the urban and nature, built on the work of sociologists at the University of Chicago, seeded a movement in the early 20th century that has dramatically taken off over the last several decades. Defined initially as "the study of the relationship between people and their urban environment" (Park, 1915, p. 578) Wu (2014) describes the evolution of this field over the 20th century. Early research drew on key theories and concepts from the biological sciences. An 'urban systems approach', understood the city to have both natural and socioeconomic aspects, and 'urban landscape perspectives' viewed the city as a heterogenous and dynamic system wherein urbanisation patterns and ecological processes interact.

More recently an 'urban sustainability approach' has emerged that explicitly couples human-environment systems. Key concepts and theories that provide the foundations for this research include: socioecological resilience, ecosystem services, complex adaptive systems, and social-ecological systems (Wu, 2014). Urban ecology as a discipline has therefore dramatically expanded its scope of study in response to a growing understanding of the multiple and interconnected dimensions of urban ecosystems.

McPhearson (2016) frames recent trends in urban ecology in terms of ecology, in, of and for cities. Ecology in cities considers how multiple ecosystem services and biodiversity needs can be met by biological systems within urban areas. In this way, ecology in cities focuses on foundation, or primary, ecological questions that were common to the work of urban ecologists in the first half of the 20th century. Many key questions remain under-explored, however, in part as a consequence of the dynamic nature of the urban spaces leading to new questions and requiring the revision of old research.

Ecology of cities incorporates the work of ecological analysis in the city, but puts forward the claim that cities themselves are ecosystems (Grimm et al., 2000; McPhearson et al., 2016). As key actors in this ecosystem, human lifestyles and living patterns, and the social structures and political processes human life give rise to, are key aspects of the analysis. In this way the traditional methods and approaches of the traditional biological sciences are required to consider approaches and ways of thinking put forward by a wider set of disciplinary perspectives, including those that come from urban studies, sociology, political science, and economics.

The integration of these disciplinary perspectives, which is understood to be on a level-playing field, necessitates systems approaches and the integration of complexity sciences (Childers et al., 2015; Groffman et al., 2017). Continued expansion of the boundaries of the field and breadth of disciplinary perspectives being brought together also requires foundational concepts and principles. Ecological principles, coming from a field that is "pre-eminently a science of synthesis and integration" (McPhearson et al., 2016, p. 204), and that is system-based (Pickett et al., 2008), as seen to fill this gap. Expanding the field of research while realising an integration of this science of cities with various modes of practice in cities, from their governance, to this design, engineering and planning, is the challenge of an ecology *for* cities in this context (Groffman et al., 2017; McPhearson et al., 2016).

The frontier of urban ecology currently lies in work bringing together social and ecology understands of urban systems, with technical and built and techno-economic understandings of the city. This research is important in the context of rapid growth of cities in the Global South, the longterm 'lockin' of urban systems physical infrastructures can cause (Ivanova et al., 2018), and the substantial role physical infrastructures play mitigating, and in other cases, extenuating, climate risks. Recent research on nature-based solutions (Xie et al., 2022), and emerging frameworks such as the social–ecological– technical/built system (SETS) approach, offer paths forward in this context (McPhearson et al., 2016.

1.2 Characterising Contemporary Science of Cities Research: Big Data, New Methods, Improved Methodologies

Contemporary urban empirical literature, a subset of which is characterised by positivism epistemologies and describes itself as science of cities literature, is a meeting place for academic thought from a diverse set of disciplines (1.2). While foundational fields of the sciences and humanities, biology and chemistry, law and philosophy, have developed over long periods of time housed in discrete parts of the university, urban empirical research has developed as a loose network across a number of disciplines over the past century. As explored in 1.4, the connections between these authors' work and the work of scholars whose fields are defined by their focus on urban settings, including some scholars of human geography and the field of urban studies, have been sporadic, poorly coordinated, and in some cases contentious. Here in section 1.3 I briefly set of unique attributes of contemporary empirical urban literature to guide the focus of the chapters that follow.

Empirical urban research by definition emphasises sensory experience and evidence, as opposed to pure reason or innate ideas, for the formation of knowledge. Science of cities literature, a subset of empirical urban research, is also usually, but not always, characterised by positivist epistemological framings that advocate for the primacy of the scientific method for knowledge generation and quantitative or theoretical rather than qualitatative approaches. Positivist epistemology emphasizes objectivity, replicability, and the use of standardized methods to produce generalizable knowledge.

The approaches of science of cities authors can also be understood in contrast with the approaches of the wider urban field. Interpretativist approaches (eg. Heinelt & Terizakis, 2021), for example, emphasize the subjective nature of urban experiences and knowledge, which conflicts with the objectivity sought in positivist methodological framings. Critical theorists (eg. Roy, 2016), for another contrast, frequently focus on social structures and power dynamics. These aspects of the urban, while sometimes emerging in the datasets of empirical researchers, are usually approached by critical theorists through the integration of diverse sets of historical, social, and political knowledges from both quantitative and qualitative sources. Postmodernist approaches to urban knowledge generation provide a further contrast to urban empirical methods. Where postmodernist approaches question (eg. Dear, 2001) foundational knowledge and deconstruct grand narratives to highlight the multiplicity of urban experiences, urban empirical researchers embracing positivist perspectives seek objective, measurable, and generalizable findings.

A dramatic increase in interest in urban questions over the last two decades can be attributed to three aspects of the methodological context in which science of cities research is being developed.

First, the development of larger, more readily accessible datasets has fundamentally transformed urban empirical research. These so-called ‘Big Data’ come from a wide range of sources including satellite imagery, sensor data from the Internet of Things (IoT), social media activity, and administrative records (Bettencourt 2021). The unprecedented volume of these data allow researchers to examine urban phenomena with greater precision and on a much larger scale than previously possible. For example, the availability of high-resolution satellite images enables detailed studies of land use changes, urban expansion, and environmental impacts (Kwan, 2018).

Second, datasets that previously would not have been available to researchers, such as those generated through crowd-sourcing and open government data initiatives, have opened new avenues for urban research. Platforms including OpenStreetMap, Googlemaps and various citizen science projects gather spatial and socio-economic data directly from the public. Higher resolution and higher quality sources of urban energy and demographic data similarly allow researchers to approaches questions that previously have required expensive and time consuming data collection. These sources of ‘better data’, realised by the development of new methods of data creation, supplement traditional data sources and can provide unique insights into urban areas, particularly in regions where formal data collection may be sparse or non-existent. These data are understood to be ‘better’ than the data sources that preceded them largely due to their being dramatically easier to access. Whether these data sources are improved in other ways, however, requires further scrutiny.

Finally, new analytical methods and methodologies, particularly those leveraging advancements in machine learning, artificial intelligence, and spatial analysis, have revolutionized the way urban data is processed and interpreted. Machine learning algorithms can detect complex patterns and correlations within large datasets that are not discernible through traditional statistical techniques. For example, deep learning models can analyze vast amounts of social media data to identify emerging urban trends, sentiments, and behaviors. Spatial analysis techniques, enhanced by GIS software, allow for sophisticated mapping and modeling of urban systems, potentially revealing spatial disparities and helping to support urban planning (Batty, 2016).

Reflecting a wider conflict in the 20st century around the nature of scientific inquiry and the value and appropriateness of scientific methods for addressing social questions (Cartwright, 1999, 2021; Hull, 1994; Klein, 1990) empirical urbanists have been at tension with wider urban community. The term ‘scientific’, for example, has been used both to criticise and to celebrate new approaches to urban research and that the ‘arrival’ of empirically-led academics to the urban field has frequently been marked by exclusionary discourse (Van Meeteren 2016).

Looking across literature that have explored the evolution of the urban field over the 20th century (Ball, 2002; Batty, 2016; Creutzig et al., 2019; McPhearson et al., 2016; Purvis, 2021; Sennett, 1996), we find two broad areas of recurring tension between established urban scholars and empirical urbanists. The first of these relates to the challenge facing empirical approaches to urban questions. The second relates to challenges of positivist epistemologies as they relate to urban research.

1.3 Challenges Facing Empirical Approaches to Urban Questions

Over the last decade concerns have been raised in a number of fields around the extent that research findings, including longstanding and sometimes 'foundational' research, can be replicated by new studies. Key aspects of this debate, on adjusting for bias, the challenge of combining information from multiple sources, and the handling uncertainty, are core problems of statistics that extend across subjects (Gelman, 2019b; Shrout & Rodgers, 2018; Yarkoni, 2022).

1.3.1 Procedural Flexibility and the Garden of Forking Paths: How Data is Collected and Analysed

Choices made around approaches to data collection, analysis and presentation have implications for the findings of research. This obvious, and tautological, statement is widely understood. Simultaneously, however, the freedom of researchers to explore sources of information, datasets, methods, what Simmons describes as "researcher degrees of freedom" (2011), is widely celebrated and typically deemed a necessary part of the research process. Problematically, very few of the choices researchers make are documented, much less are choices considered in a systemic way. Consequently, research frequently progresses down a "garden of forking paths" where it becomes impossible for a researcher to determine if choices led to minor or massive implications for study findings (Gelman & Loken, 2014).

Research has found that the consequences of seemingly minor changes in research processes can lead to substantial changes in research findings. Simmons et al (2011), for example, find that even small changes in the choice of dependant variable in an analysis, or around the functional form of an analysis could lead to more than half of studies generating false-positive finings. Similarly, Strube (2006) finds that the practice of stopping data collection at a point where statistically meaningful findings have been found has the potential to increase the rate of false-positive findings.

The challenge, and debatably the trade-off, between facilitating exploration while maintaining academic, theoretical and statistical integrity, exists as a fundamental challenge for the statistical sciences (Gelman, 2019a). In the context of urban research, where the growth of data sets and research methods are seen as a source of opportunity for addressing climate and wider challenges in cities (Creutzig et al., 2019), these issues may be particularly large.

A lack of awareness of the nature of the information being used for and generated by empirical work is a fundamental epistemological problem that manifests in the form of biases and blindspots. While semantically these terms have a similar meaning I differentiate between them in order to order to distinguish between cases where it is known that a dataset has limitations (a 'bias') and cases where the limitations of the dataset are not known (a 'blindspot').

1.3.2 Biases and blindspots

Vast amounts of information from connected devices are an inescable feature of the modern world. The value of this data from a public policy or research perspective, however, does not naturally follow from the enthusiasm of individuals and firms (Khan et al., 2020). So called 'Big Data' generally provide a restricted number of variables, requiring assessments to draw inferences with explanatory characteristics (Hu & Jin, 2017). The ways algorithms capture, sort, clean and pass on data can alter our understanding of phenomena in ways that policymakers (and sometimes information providers) are not aware of (Zou & Schiebinger, 2018). Modes of governance informed by such data can incentivize local governments to prioritize a narrow set of metrics (Hughes et al., 2020) and to discount wider means of urban knowledge generation (Coletta and Kitchin 2017). And what data is available, for who and under what circumstances remains a legally and ethically contentious question, with a number of authors reminding us that it would be naive to assume that the interests of private firms automatically align with the interests of the wider public (Albino et al., 2015; Docherty et al., 2018; Wang & Ma, 2021).

Some empirical urban authors claim biases in datasets and published research was mainly an issue of the 19th and 20th centuries (eg Lobo et al., 2020). In conflict with this claim wider literature document how information on the urban continues to be focused towards the Global North (Nagendra et al., 2018), towards male perspectives and experiences

(Khreis et al., 2016), towards the economic and financial over the social and environmental (Gouldson et al., 2018), and towards those with higher socioeconomic status (Colenbrander et al., 2017), among other ways. Bias in datasets, which can blinding policymakers to the impact of policies on particular populations, therefore remains a significant challenge for urban empirical research (Kwan, 2018).

Questions surrounding the value of new sources of data for policymaking thus extend from the specificities of data collection techniques and the ways algorithms are developed to overarching logics and rationalities and their implications for governmentalities (Bissell, 2018; Coletta & Kitchin, 2017; Kitchin et al., 2015). Empirical urban research demonstrating uses of urban datasets are growing almost as fast as the datasets themselves, but careful consideration of the ways in which these new data, and the methods accompanying the exploration of this data, advance (and fail to advance) our understanding of urban environmental challenges is lacking.

1.4 Challenges facing Positivist Approaches to Urban Questions

Antecedent to many of the challenges empirical urbanism pose to science of cities literature are a set of challenges originating from the epistemological approaches that underpin much of empirical urban research. Specifically, the dominance of positivist research traditions in science of cities authorship may raise challenges investigating urban questions.

1.4.1 Construct Validity: The Extent Hypotheses can be Operationalised by Quantified Approaches

The abstract and at times subjective nature of urban concepts challenges positivist epistemological approaches that seek objectivity and measurability in phenomena. This complexity requires researchers to grapple with diverse definitions and frameworks to ensure comprehensive and valid measurements. In the context of urban transitions and climate change, the concept of capacity exemplifies these challenges in the way the definition of capacity changes across studies and contexts (eg Castán Broto et al., 2019; Filho et al., 2018; Gouldson et al., 2016; Wolfram et al., 2019). Similarly, the concepts of social sustainability (Opp, 2017) and environmental sustainability (Purvis et al., 2019) exemplify the multidimensionality and disputed nature of environmental and urban concepts.

Even where concepts are seemingly less subjective, processes of operationalisation can lead to significant impacts on the way we understand phenomena. Giljum et al. (2019), for example, explores global material use is operationalised in Global Multiregional Input–Output models and find that material use estimates vary significantly as a consequence of choices of model inputs.

Further complicating this issue is the need for researchers to reconcile theoretical frameworks with empirical validation. Establishing validity in urban research involves not only ensuring that measurement instruments comprehensively cover the construct's domain but also addressing the subjectivity inherent in defining and operationalizing these constructs. This process necessitates iterative refinement, expert judgment, and integration of diverse perspectives to develop robust and reliable instruments.

1.4.2 The Privileging of Patterns over Processes

Gelman and Imbens (2017) raise the challenge of positivist research approaches predominantly focusing on the effects of causes rather than the causes of effects, a distinction between research approaches originally identified by John Stuart Mill. Gelman and Imbens go so far as to suggest (2013, p. 1) some researchers “dismiss the search for causes as "cocktail party chatter" that is outside the realm of science”. Along similar lines Manson and O’Sullivan (2006) discuss the limitations of research that privilege pattern identification over process identification.

Recent critiques highlight how this privileging of patterns over processes particularly affects urban knowledge generation in the era of big data. Hogn et al (2023) argue that while big data analytics can reveal patterns at large scales, such approaches may struggle to capture more nuanced and contextualized forms of knowledge. This limitation is especially problematic for understanding urban processes that occur outside formal or digitally-traceable systems, or in contexts where technological coverage may be less comprehensive. The focus on discoverable patterns through big data thus risks missing crucial urban processes, particularly those involving marginalized populations or informal activities

Quantitative research is empowered with a range of tools for teasing out patterns of action and interaction. The scale of datasets, the extent researchers can impute and control specific aspects of context, and advanced methods of analysis, however, are not necessarily enough to overcome the challenges of causal inference outside of experimental settings (Gordon et al., 2022). Indeed, in settings like urban areas, where researchers will rarely have meaningful control over the first of these two considerations, the challenge of approaching causal questions will be raised even higher.

A focus towards effects and patterns rather than causes and processes, however, is more than a matter of avoiding hard questions. Yarkoni and Westfall (2017) note that there is often an implicit notion when the tools of natural sciences are applied to the social sciences that causes and effects are so intertwined that their separation is more a philosophical than practical exercise. Identifying patterns via the use of standardized models and framings from theories of complexity is increasingly seen as the foundation of analytical approaches to evidence-based analysis of questions with mixed social and natural aspects. The most ideologically pure of this wave of new scientists claim not only neutrality in their methods of analysis, but in the data itself, which is claimed to be able to "speak for itself" (Anderson, 2017; Villanueva et al., 2016).

Westman and Castan Broto (2022) argue that a focus away from foundational questions and towards proximate and poorly defined topics such as 'urban transformations' may be fertile ground for discourses and problematisations being co-opted by those who are opposed to structural change (Westman & Castán Broto, 2022). More generally, a bias towards generalisable patterns, and 'laws', privileges that aspects of cities that can be measured, observed and are common across cities over the social, political, cultural that are hard to measure or unique across cities. In other words, the aspects of 'place and space' (Manson & O'Sullivan, 2006) that may be critical to understanding urban environmental transition may be lost.

1.4.3 De-politicisation, Determinism, and the Crowding out of Alternative Perspectives

Climate policies widely perceived as having neutral or negligible welfare implications can have significant distributional impacts, potentially exacerbating existing inequalities (Owen et al., 2022; Owen & Barrett, 2020). Simplifying complex social phenomena into measurable components and assessing those components in a manner that can be replicated, as called for by positivist epistemologies, can therefore lead to key sources of knowledge being left out of analyses.

Purvis (2021) notes that so-called 'neutral' approaches to urban science are key to enabling the development of systematic approaches. Whether a neutral or 'de-linked' analysis of phenomenon with social aspects is possible, however, is questioned by Gelman, who posits that political and normative considerations are simply embedded rather than removed in scientific methods and arguments (Gelman, 2019b; Grätz, 2018; Hardwicke & Ioannidis, 2019). Economic valuation approaches can depoliticize these issues by reducing complex social and cultural values to monetary terms, potentially crowding out alternative perspectives and ways of understanding these conflicts (van der Horst & Vermeylen, 2012)

Brenner and Schmidt, speaking to his interpretation of these embedded normative and political aspects suggests, "neo-positivist, neo-naturalist approaches represent a revival of important strands of postwar systems thinking in geography, planning and design discourse, which had been closely aligned with national state projects of urban social engineering and territorial control" (p.157, 2015). Along similar lines Gleeson calls such approaches "part of a broader technoscientific ideology that aims to depoliticize urban life and thus 'to assist the cause of sound management'" (p

348, 2014). Gleeson and Brenner are thus among a critical urban scholarship who interpret a limited focus on political factors – as a consequence of the 'piranha problem', the challenge of quantifying political variables, or otherwise – as part of a discursive framing designed to legitimise a neoliberal agenda (Brenner and Schmidt, 2015).

The rush to establish normative conclusions in positivist approaches creates another form of depoliticization - one that occurs through skipping over crucial meta-ethical questions about what concepts mean in different contexts. As Winkler and Duminy (2016) argue, while planning theory has embraced epistemological diversity, it has failed to adequately examine how foundational concepts like 'improvement' or 'better outcomes' are understood differently by various stakeholders and communities. This meta-ethical blindspot allows normative assumptions to masquerade as universal truths, further contributing to the depoliticization of urban research.

Connected with concerns over the de-politicisation of the urban are concerns that the application of modelling techniques derived from asocial phenomena may lead to a deterministic representation of urban processes and change. The crisp distinctions derived from positivist research approaches are widely argued by urban researchers to clash with the fluidity, spontaneity, and messiness of the real-world urban (Castan Broto, 2020). More importantly, by identifying rules and axioms of the city, mathematical representations of the urban are seen to give the impression of voiding urban stakeholders of agency and responsibility. Purvis (2021) problematizes the divide between critical urban studies and more positivist 'urban science' approaches, suggesting that this disconnect may inadvertently contribute to the depoliticization of urban research by ceding ground to neoliberal technocratic approaches

Literature exploring the governance of urban climate action most strikingly conflict with the work of empirical urban research in this regard. Authors who approach urban settings from the perspective of multi-level governance, for example, make coordination and communication between actors, differentiated authority, capacities to act, and political and legal contexts, the foundation of their work (Betsill & Bulkeley, 2007; Fuhr et al., 2018). Similarly, a burgeoning 'place-based' authorship set as the foundation of their authorship the need for, and benefit of, localised understandings of and responses to challenges such as climate change (Creasy et al., 2021). Foundational for these authors, therefore, are not fundamental aspects of the urban that (may) have existed for millenia and that are usually quantified, material aspects of urban areas, but place and time specific qualitative characteristics of the urban.

Connecting these criticisms are a divide over the essence of what scholars understand as "the urban". Brenner (2015) makes the case that "a singular ontological position regarding the underlying essence of cityness" (p. 152), found in positivist urban literature crowd out alternative ways of understanding the urban. More generally, the hegemonic status of the science, technology, engineer and mathematics (STEM) fields in the minds of the public and policymakers is seen to aid the expansion of positivist and empiricist approaches to urban questions (Cauvain, 2018; Opp, 2017; Petts et al., 2008).

1.5 Research Rationale

Enthusiasm for the advancement of a 'science of cities' is high. A science of cities is seen to have the potential to help us respond to a global Climate Emergency (Creutzig et al., 2019) and to support the wider project of a transition to sustainability (Acuto et al., 2018; Purvis, 2021). Urban science is also thought to help us to understand the combined technical, social, political and ecological nature of cities towards the development of a more integrated and multidisciplinary urban field (Folke et al., 2016; Grimm et al., 2015; McPhearson et al., 2016; Meerow et al., 2016).

However, the extent to which empirical positivism applied to the urban today has overcome the challenges they have faced across the 20th century is not clear. Datasets, though vastly superior to those of the early century, continue to face a challenge capturing aspects of the urban, and key urban ideas and concepts continue to be challenging to capture and test by empirical means. More fundamentally, cities, both in the real and academic worlds, are a meeting point. The richness of the city, as well as its complexity, come from the range and diversity of things it encompasses, demanding means of interdisciplinary collaboration and learning for our understanding to progress. Similarly, environmental challenges of the 21st century are knots with social and political as well as technical and economic threads, demanding means for knowledge to be brought together from diverse disciplines.

The challenges facing empirical and positivist ontologies when applied to subjects that have traditionally been led by scientists from the humanities and social sciences is well described (see Cartwright, 1999; Hull, 1994; Klein, 1990). Understanding in detail how an a science of cities in its modern form is challenged as it engages with urban environmental challenges, however, is important for two reasons.

First, there is a strongly held and widely voiced opinion that contemporary positivist urbanism has overcome foundational and longstanding challenges. Karvonen (2021), for example, writes that the "divide between the natural and social sciences has been bridged with an updated systems perspective" (p. 5). Similarly, describing how current empirical urban research is unique from what preceded it Lobo (2020), writes, "the study of cities and urbanization within many distinct disciplines has reached a productive level of methodology, data, and findings" (p.9). In the context of a closing window of opportunity to prevent dangerous climate climate, considering if these assertings are true is critically important to orienting research towards the questions that can most rapidly advance urban environmental knowledge.

Second, calls for integrated academic approaches to urban environmental challenges have been made and repeated (Acuto et al., 2018; Groffman et al., 2017; McPhearson et al., 2016; Solecki et al., 2013). These calls reflect a widely held understanding that urban environmental challenges benefit from diverse sources of knowledge. In some cases these authors makes the case that diverse sources of knowledge are not just beneficial but necessary for advancing urban knowledge and addressing urban environmental challenges (Creutzig et al 2024). The repeated nature of these calls, however, underlines that integrated approaches remain unrealised. In this context, defining the challenges facing science of cities researc can help to help to understand epistemic conflicts that need to be addressed for the realisation of an integrated urbanism.

1.6 Aims and Objectives

The overarching purpose of this thesis is broad; I seek to interrogate science of cities research to understand its contribution to action on urban environmental challenges and to the wider urban subject. To this end I set out three objectives, each developed around one of the characterising features of contemporary empirical urban literature:

1) To use a case study of the application of Big Data for urban environmental challenges as an opportunity to reflexively consider how Big Data sources are (or are not) advancing knowledge and practice for addressing urban environmental challenges.

2) To use a case study of the application of new methods related to urban environmental challenges as an opportunity to reflexively consider how these methods are (or are not) advancing knowledge and practice for addressing urban environmental challenges.

3) To develop a case study that considers new methodological approaches to urban environmental challenges as an opportunity to reflexively consider how new approaches are (or are not) advancing understanding of urban environmental challenges. While Chapter 2 focuses on specific methods, Chapter 3 considers collections of methods which form a larger framework or approach to an urban empirical question.

Figure 1 shows where the characteristics of contemporary empirical urbanism may intersect with longstanding challenges facing empirical approaches to urban questions and how each of these aligns with the focus of a chapter in this PhD. Each of these challenges will to greater and lesser degrees exist in all empirical research. In specific case studies, however, there may be a unique opportunity to focus on some of these challenges.

Table 1-1: The intersection between longstanding challenge facing empirical methods applied to urban questions, the characteristics of contemporary science of cities research, and the chapters of this thesis

		Characterisation of contemporary science of citiesl research		
		Bigger data	New methods	Improved methodologies
Longstanding challenges of applying empirical approaches and positivist epistemologies to urban questions	1.4.1.1 Procedural Flexibility and the Garden of Forking Paths: How Data is Collected and Analysed	X	X	X
	1.4.1.2 Biases and blindspots	X	X	X
	1.4.2.1 Construct Validity: The Extent Hypotheses can be Operationalised by Quantified Approaches			X
	1.4.2.2. The Privileging of Patterns over Processes	X		X
	1.4.2.3 De-politicisation, Determinism, and the Crowding out of Alternative Perspectives	X	X	X
		Chapter 2: Fair Weather Forecasting? The Shortcomings of Google Maps for Transport Planning, a case study from Huballi-Dharwad, India	Chapter 3: Data Scaling: Implications for Climate Action and Governance in the UK	Chapter 4: Climate policy as social policy? A comprehensive assessment of the economic impact of climate action in the UK

The challenges associated with unmarked decisions (1.4.1), including those decisions that are explicitly made by researchers and those assumptions made unknowingly, exist across empirical urban literature. These issues are potentially most significant, however, in applications of ‘Big Data’ (Chapter 2) and ‘Better data’ (Chapter 3) where steps in the collection, cleaning, and sharing of data introduce opportunities for unmarked decisions.

The biases and blindspots (1.4.2) created as a consequence of empirical representations of urban potentially missing key aspects of the context or subject similarly exist across all empirical urban research. A focus on this challenge may be relatively larger in Chapters 2 and 4. The scale and novelty of ‘Big Data’ (Chapter 2) may blind researchers and policymakers to the extent these data fails to capture aspects of the context or subject and the introduction of new methods can lead users to assume biases and blindspots have been addressed.

The extent hypotheses can be operationalised by quantified approaches (1.5.1) may be uniquely highlighted by literature exploring new methods and methodologies. Operationalisation of urban concepts arises with the use of Big Datasets (Chapter 2) and with the use of ‘better data’, however the process of operationalisation is itself a method. Where new methods and methodologies are highlighted by urban empirical author may therefore be the clearest opportunity to engage with operationalisation as a fundamental challenge for urban empirical research.

A privileging of patterns over processes (1.5.2) may be uniquely brought forward in applications of Big Data (Chapter 2) and new methods and methodologies (Chapter 4). Large datasets are essential for developing and testing the ‘rules’ and ‘fundamental principles’ of cities that are the focus on some empirical researchers. Testing for these ‘rules’ and principles, however, necessarily privileges patternsmaking over the exploration of causal inference (Anderson, 2017; Villanueva et al., 2016). At the same time new methods and methodologies (Chapter 4) in some cases target the challenges of using empirical data to explore causality.

Depolitisation, determinism and the crowding out of alternative perspectives (1.5.3) exists as a foundational challenge for empirical and positivist epistemologies. In the context of contemporary empirical urban research this challenge is uniquely brought forward by any of the characteristics of contemporary empirical urban research, however the way this challenge manifests may be unique across these cases.

1.7 Design and Methods

The research in this PhD is designed to be reflexively critical. By applying the empirical and positivist approaches that characterise contemporary science of cities environmental literature, I seek to acknowledge and critically evaluate the limitations, assumptions, and potential biases inherent in those approaches. In each chapter a quantitative methodological approach is employed reflecting the approach of the majority of empirical urban environmental research.

In Chapter 2 I develop a case study to explore the value of Big Data for understanding urban environmental questions. To explore this question I use the Google Maps® Application Programming Interface (API) to estimate travel times before and after the introduction of a new bus-rapid transit system between the urban centres of Huballi and Dharwad in India. From 206 cells (or areas) covering Huballi and Dharwad I collected data for both the trip time and distance every hour from 5am to 11 pm from April 2018 to mid-July 2018 developing a dataset of several million estimated journey times.

Huballi-Dharwad represents a case where the use of new data and approaches may be uniquely valuable. Huballi-Dharwad is growing rapidly, both in urban scale, population and level of economic development. This growth is creating challenges for the provision of infrastructure and services and also creates challenges for conventional approaches to urban transport analysis which can take months to years to complete (Nicolaisen & Driscoll, 2014). Further, Huballi-Dharwad is in India, a country that has been particularly enthusiastic about the use of Big Data and novel technical approaches to informing policymaking. Finally, the dataset is collected through Google, which in turn is collecting its data from mobile phone users in Hubbali-Dharward. The layers of human interaction (the people in Huballi-Dharwad, the workers at Google and myself and the research team), and the methodological processes, raise complex ethical and political as well as technical questions that support a wider discussion about the role and value of big data for urban knowledge generation.

In Chapter 3 I develop a case study that considers how development in methods of data analysis may be able to support the development of urban knowledge and practice as it relates to urban environmental questions. To consider this question I look at local area Greenhouse Gas (GHG) datasets in the UK. Gathering local data in the UK, as in many other countries, long required substantial effort on the part of part of researchers. Recent work by the UK government and academics, however, have made multiple datasets of local level GHG data readily available.

Two datasets are used in this analysis. The first consists of 32,844 emissions footprints from Lower Layer Super Outputs Areas (LSOAs) covering 12 sources of emissions. LSOAs are a geographic designation that includes an average population of 1500 people. This dataset was developed by the Centre for Research into Energy Demand Solutions (CRED) and is available from their place-based carbon calculator (CRED 2021). The second dataset consists of territorial emissions across 407 local authorities between 2005 and 2021 (BEIS 2023). Local authorities have an average population of approximately 165,000.

In Chapter 4 I explore how new methodologies affect our understanding of urban environmental challenges. To approach this question I develop an extended version of the so-called 'mini Stern' methodology. (Gouldson et al., 2015a; A. H. Sudmant et al., 2017; Williamson et al., 2020). Named after the Stern Review (Stern, 2007), a landmark report on the economics of climate change in the UK, 'Mini Stern' analyses consider the economic case for climate action within a defined city or region using techno-economic models of low and zero carbon climate action interventions. In the analysis I conduct I extend the existing methodology by including co-benefits of climate action as well as the direct benefits of climate action. These co-benefits include the value of cleaner air, reduced congestion and warmer homes. Analysis covers six urban regions which were selected to capture the diversity of urban contexts in the UK, including urban regions from each of the four nations (Scotland, Northern Ireland, Wales and England) and from cities with both relatively larger and smaller industrial sectors. The six urban regions are Glasgow, Belfast, Swansea Bay, Liverpool, Greater Manchester, and Cambridgeshire and Peterborough.

1.8 Reflections on my Academic Journey: Situating This Thesis

The development of this thesis was unique from conventional approaches to doctoral research, including standard "PhD by publication" paths. While many structured PhDs by publication build systematic arguments through deliberately sequenced publications, this research emerged through engagement with various academic and practitioner-oriented projects over an extended period.

This thesis was written over the course of 8 years, 7 of which I was employed by Leeds University. During my time at Leeds I had the opportunity to contribute to, and in some cases lead, a wide range of projects. The first projects I worked on were assessing the economics of urban climate action in Malaysia, Indonesia and Peru. Following this I worked in Brazil, Rwanda, China, and Canada then (finally) to work on urban climate action in the UK. I graduated from conducting economic analysis to leading economic analysis and the work shifted from focusing on finance to economics to public value. The work shifted from quantitative and disciplinarily well defined, to mixed methods and interdisciplinary and audience of the projects moved from academia to public policymakers, NGOs, and members of the public.

I am deeply grateful for the opportunities I have had. I deleted and rewrote the list of countries in the previous paragraph several times out of concern that it might seem I was bragging. It also is not ideal to have a list like that at the head of a thesis about climate change. I left the list in because it neatly captures how fortunate I was to join Professor Gouldson's research team and for him to have put me in charge of leading different parts of his work.

This journey shaped my thesis and my experience of writing it. The different projects, contexts and audiences were collectively a sort of alternate advisor. An advisor with a lot of great ideas, but far too many for one thesis, a lesson I only started to learn around year 6. Negotiating between work and studies is the basic challenge of a part-time PhD and a challenge that I am not sure is necessarily made easier if your work and studies have similar themes and topics.

Overlapping ideas and perspectives, complimenting and conflicting, added stress and time to my thesis but exposed me to the epistemological tensions that lie just beneath the surface of any urban environmental research. Working across different projects and having the time to develop my own methodological 'toolkit' also helped me realise how methodological choices reflect deeper normative positions about what constitutes valid knowledge. My methodological thinking has evolved substantially across the included papers. The paper that is now Chapter 2 began as a relatively straightforward application of quantitative methods but moved toward a more critical interrogation of the data and whose experiences it could capture. Chapter 3 represents a more deliberate engagement with how methodological choices shape our understanding of environmental challenges but was enabled by the skills and insights from years of working on urban carbon accounting and urban climate action projects. Chapter 4 marks a further evolution, explicitly exploring how normative assumptions shape empirical findings.

From a larger body of publications where I served as lead author, I selected three papers that collectively capture the evolution of my thinking about quantitative empirical urbanism and best represent the central questions explored in this thesis. This selection process involved careful consideration of how each paper engages with the characteristics of contemporary quantitative urban environmental literature identified in section 1.3: Big Data, new methods, and improved methodologies.

I sought papers that would illuminate different aspects of the epistemological challenges facing empirical urban research. The Google Maps study in Huballi-Dharwad (Chapter 2) was selected because it demonstrates both the opportunities and limitations of Big Data approaches in urban contexts, particularly highlighting the challenge of unmarked decisions and biases in data collection. The data scaling paper (Chapter 3) was chosen for its exploration of how new analytical methods can systematically affect our understanding of urban environmental challenges, revealing how seemingly technical methodological choices can embed political and normative positions. The co-benefits analysis (Chapter 4) completed this trajectory, directly engaging with how normative decisions influence empirical analyses even within seemingly objective analytical frameworks.

Together, these papers tell a story about the evolution of quantitiative empirical urban environmental research and its limitations. They also demonstrate a progression in my own approach—from applying empirical methods somewhat uncritically to developing a more nuanced understanding of how they might be integrated with other ways of knowing the urban. Other publications in my portfolio, while valuable in their own right, did not as clearly demonstrate this particular intellectual journey or engage as directly with the epistemological questions at the heart of this thesis.

In presenting this thesis, I therefore offer not only research findings but also a reflection on the research process—how it is shaped by institutional contexts, methodological traditions, and evolving theoretical understandings. While this approach has required retrospective construction of coherence, it offers unique insights into navigating the epistemological divides characterizing urban environmental research. The most valuable outcome of this thesis for me lies in this meta-analytical perspective on the research process itself. My PhD by publication journey, extending across diverse projects and evolving over time, provided fertile ground for critically examining how methodological choices and epistemological commitments shape our understanding of urban environmental challenges—insights that might have remained elusive in a more conventional doctoral program.

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2 Fair Weather Forecasting? The Shortcomings of Google Maps for Transport Planning, a case study from Huballi-Dharwad, India

India ranks among the countries that has most embraced the idea of the 'Smart City', however case study literature focused on the public policy implications of 'Smart' and 'Big Data' interventions in India is currently limited. This paper contributes to this gap by investigating the value and limitations of Google Maps® data for evaluating transport policies, plans and projects in Huballi-Dharwad, India. Results suggest that Big Data from Google Maps® may enable the outcomes of transport interventions to be evaluated much more readily. However, the analysis also found that this data may be less able to detect the impacts of travel behaviours in informal settlements or the impact of extreme weather events. These shortcomings, coupled with the lack transparency around the methodology and sources of the Google Maps data, raise significant concerns around the potential for unintended consequences and biases in the use of these data sources for public policy. Reflecting on the wider challenges urban analytics face, we conclude that there is an urgent need for 'Big Data' and other technical advances in urban modelling to be seen as compliments rather than substitutes for wider methods of knowledge generation in urban areas.

Sudmant, Andrew; Viguié, Vincent; Lepetit, Quentin; Oates, Lucy; Datey, Abhijit; Gouldson, Andy; Watling, David

2.1 Introduction

Whether urban growth contributes to solving, or aggravating, a wide-range of global challenges will be significantly determined by the urban transport networks. Design well, transport networks can increase the effective density of urban areas, allowing people to access jobs (and employers to access employees), residents to choose public and non-motorised mobility over cars, and governments to cost-effectively provide basic services and public amenities. Designed poorly, transport networks can choke an urban area's economy and lead to sprawl, congestion and pollution, making urban dwellers worse off than their rural counterparts.

The cost of congestion in urban areas today, a symptom of transport networks failing to meet demand, is greater than 1% of GDP in European and North American cities, 2-5% of GDP in cities in many Asian and Latin American cities and as high as 15% of GDP in Beijing, China. While congestion is a global challenge, its costs are most acutely felt in the developing world (Cookson and Pishue, 2017; Mao et al. 2012; Creutzig and He 2009).

Whether public transport interventions exacerbate or ameliorate this challenge will be determined in part by the ability of policymakers to rapidly assess the potential for transport interventions, particularly those that discourage private transport options, and to draw lessons from completed projects. Such assessments, however, face a range of challenges, from overly optimistic modelling processes, to problems with data access, to the complexity of modelling urban mobility processes (Gouldson et al 2018). Consequently, high quality ex-post assessments of transport interventions that could yield important insights are rare even in wealthy nations (Flyvbjerg, Holm, and Buhl 2003; Nicolaisen and Driscoll 2014; Driscoll 2014). In urban areas in low income countries, where annual city budgets can be less than 20 USD per inhabitant and population and vehicle ownership are rising quickly, addressing this challenge has particular urgency (Cabannes and Lipietz, 2015; Ibrahim, Haworth and Cheng, 2019; Sudmant et al 2017).

In this context, tremendous potential is thought to exist from harnessing 'Big Data': The vast amounts of information coming from mobile phones and other connected devices that are increasingly ubiquitous to our lives. Real-time, geolocated, high frequency and (in many cases) low cost applications of Big Data for transport – including Google Maps®, Waze, Apple Maps, TomTom and a host of other services – are already used by billions on a daily basis, ostensibly demonstrating that they are valued by individuals and businesses.

The value of such data from a public policy context, however, does not naturally follow from such services being widely used by individuals and firms. Big Data sources generally provide a restricted number of variables, requiring assessments to draw inferences with explanatory characteristics (Hu and Jin 2017). Datasets can be biased, blinding policymakers to the impact of policies on particular populations (Kwan 2018). The ways algorithms capture, sort, clean and pass on data can alter our understanding of phenomena in ways that policymakers (and sometimes information providers) are not aware of (Zou and Schiebinger 2018). And what data is available, for who and under what circumstances remains a legally and ethically contentious question, with a number of authors reminding us that it would be naive to assume that the interests of private firms automatically align with the interests of the wider public (Docherty, Marsden, and Anable 2018; Albino, Berardi and Dangelico, 2015).

Nonetheless, building 'Smart Cities' has become a national policy objective in a number of countries worldwide. In India, the 'Smart Cities Mission' was launched in 2015 to seek improvements in quality of life, the environment and governance, largely through the application of information and communication technologies (Dwevedi, Krishna and Kumar 2018). The 'Smart Cities Mission' is focused on 'second-tier' cities (Shukla, Balachandran and Sumitha; 2016), and particular opportunities are thought to exist in the transport sector and from new sources of 'Big Data', including Google Maps (Chandiramani and Nayak, 2019; Rakesh, Heeks and Chattapadhyay 2018). Huballi-Dharwad is among the 100 cities in the 'Smart Cities Mission', and 'Smart Mobility' is recognised as a key area for intervention (Hubbali Dharwad 2020).

A growing body of research has considered the role of Big Data for transport research and planning (Batty, 2012; Calabrese et al. 2013; Milne and Watling 2019) with a branch of this research focusing specifically on Google Maps® data (Hanna, Kreindler, and Olken 2017; Kreindler 2016; Dumbliauskas, Grigonis, and Barauskas 2017; Akbar and Duranton 2017; Akbar et al., 2018). This article adds to this research in two ways.

First, by focusing on a smaller urban centre in the Global South this research considers an underexplored context. In contrast with the larger and often wealthier urban centres that are the focus of much existing research, smaller urban centres frequently have very high urban growth rates and have yet to invest significantly in public transport networks. Such urban centres are also more likely to face capacity issues in government due to smaller budgets and less established institutional structures, possibly leading them to be more attracted to 'smart innovations' using Big Data. Cities with these characteristics are anticipated to be the source of the majority of urban population growth over coming decades (UN DESA 2019).

The potential value of Big Data to transport planning in Huballi-Dharwad, and 'second-tier' global cities more generally, is considered in the first and second section of the Results. A first analysis assesses the extent that the Google maps data in this analysis can provide information on key attributes of the transport system including hourly and weekly travel times on key routes. Following this, the second section of the Results provides an assessment of the impact of a new bus-rapid transport line.

The second way this analysis adds to existing literature is by probing some of the specific potential shortcomings of 'Big Data' raised by existing authorship. The third section of the Results assesses the possibility that algorithms may capture, sort, clean and pass on data in ways that alter our understanding of phenomena (Zou and Schiebinger 2018) by focusing on a major rainstorm event that affected Huballi-Dharwad in June 2018. Finally, the fourth section of the Results assesses potential biases in the data (Kwan 2018) by comparing the quality of the data provided from slum and wealthier parts of the city.

2.2 Study area

A rapidly expanding urban population and sprawling cities are placing increasing pressure on transport systems in India. At the same time, partly as a result of increasing incomes, there is a growing trend towards private transport. The transport sector contributes to about 15% of CO_2 emissions in India, a share that has been increasing over time (Tiwari 2011) and congestion, air pollution and road traffic accidents are common in urban areas, at great cost to society and the economy.

The National Urban Transport Policy (NUTP) of 2006 emphasised the need to give greater priority to public transport, and the Sustainable Urban Transport Program (SUTP) was designed to support and demonstrate the principles of the NUTP. Following the adoption of these policies, a Bus Rapid Transit (BRT) scheme connecting the twin cities of Huballi and Dharwad was chosen as a demonstration project. The engineering study completed before construction contains many of the 'best practice' elements for BRT networks. For example, the system is designed with a dedicated roadway, raised platforms, a limited number of stations and an electronic payment system. Importantly, the document also highlights that reducing congestion along the main corridors of the city is a key justification for the project (CEPT 2013). Assessing private vehicle travel times along the route is therefore seen as an indirect means of assessing the success of the project and its overall impact on the city' transport network.

Whether Google Maps® travel time estimates (or other Big Data sources) can be used in this way has relevance beyond Huballi-Dharwad. BRT systems are considered an important tool for climate change mitigation due to their potential to provide an important public service whilst also contributing to global emissions reduction targets (IEA, 2013). Studies from several cities with well-established BRT systems - such as Bogota (Turner et al, 2012), Johannesburg (JIKE, 2012) and Mexico City (INE 2008) - substantiate this. In addition, they contribute to the reduction of air pollutants such as carbon monoxide and particulate matter, primarily through reducing the total number of vehicle kilometres travelled and by encouraging the replacement of older, smaller vehicles with newer, cleaner high-capacity buses (Carrigan et al, 2014). Research also suggests that BRT systems can contribute to equity objectives by providing low-income groups with greater access to public transport, travel time and cost savings, and safety benefits (Venter et al 2017).

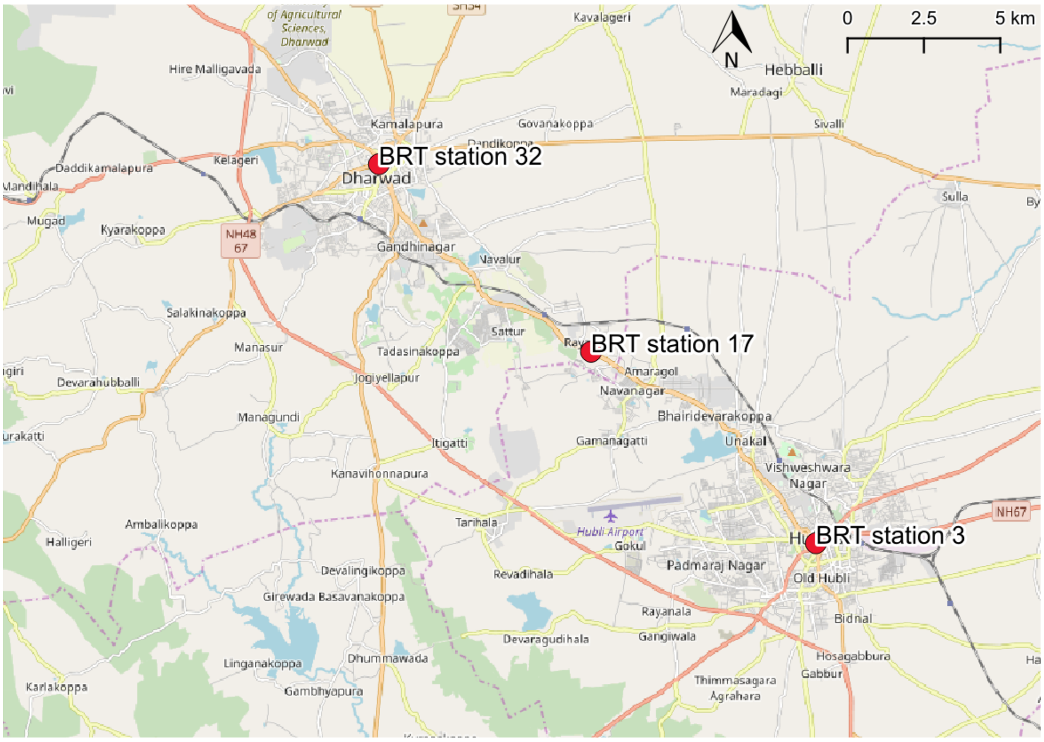

Figure 2-1: Map of Huballi-Dharwad and its BRT stations

With a population of 940,000, Huballi-Dharwad municipal area is the second largest urban agglomeration in Karnataka State after Bangalore. Huballi is the region's commercial centre while Dharwad is the administrative and educational hub (UNESCAP 2014). A BRT was proposed as a way to improve connectivity between the cities - which are around 20 km apart - and to temper vehicular growth, while accommodating an urban population that is projected to reach almost 1.5 million by 2030 (ibid). After delays resulting from complex land acquisition processes, the Huballi-Dharwad BRT began operations in October 2018.

Almost one fifth of the population of Huballi-Dharwad lives in slums (Ministry of Housing and Urban Affairs 2019). This is significant in the context of this research since slums have fewer vehicles that Google can track to determine travel times, and residents may have fewer devices from which Google can collect data. A recent study from Karnataka's capital, Bangalore, shows that less than 1% of slum households own a car (Roy et al 2018), compared with more than 70% of wealthier households in the same city (Bansal et al 2018). Assuming this is representative of cities in India, this could make it potentially challenging for Google to estimate travel times from these areas, a matter we investigate at the end of the Results section.

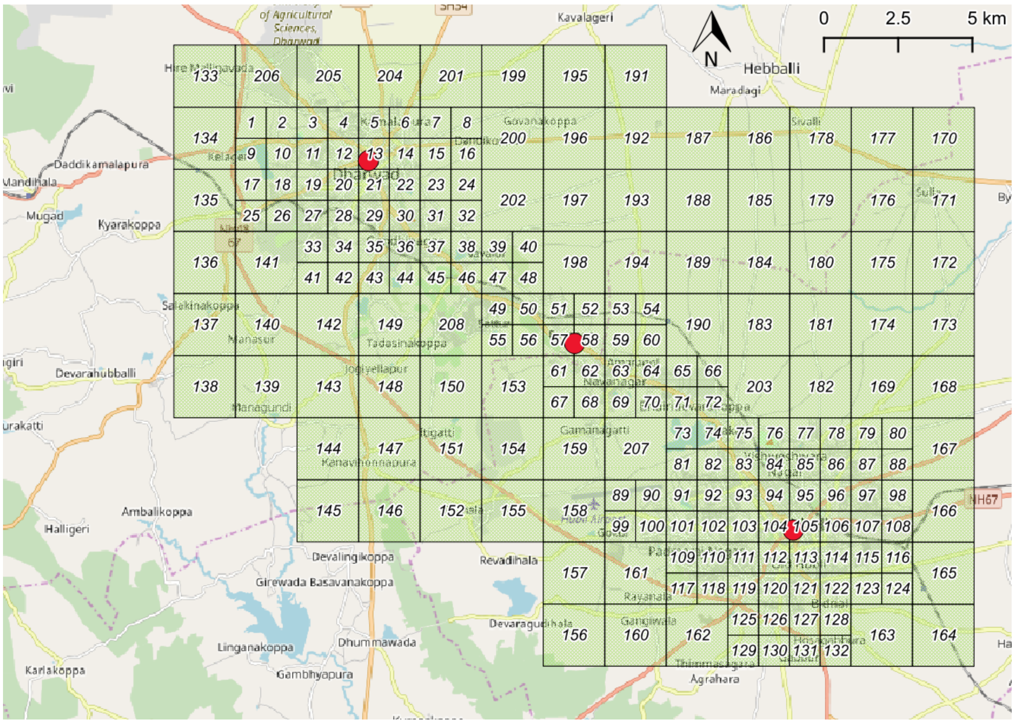

Figure 2-2: Grid points used in the analysis (background map: OpenStreetMap, 2019)

2.3 Methodology

A set of measurements was conducted through Google Maps® Application Programming Interface (API) queries with information collected on estimated live travel trip durations and distances. Three of the 33 new bus stations that are part of the BRT were selected as departure and arrival points: The Chennamma station located in the centre of Huballi; ISKCON located in the middle of the BRT pathway and near the main hospital; and Jubilee Circle in the centre of Dharwad. In addition, an analysis grid of 1 and 2 kilometer resolutions covering the urban area of the city was built around the bus stations comprising 206 grid cells. Queries for both the trip time and distance from each grid cell to each of the centres and each centre to each grid cell was conducted every hour from 5am to 11 pm from April 2018 to mid-July 2018. From mid-July 2018 queries were limited to Tuesday and Thursday until mid-February 2019.

Although Google Maps®' estimated time of arrival algorithm is not public, it is understood that Google uses different features to assess live travel times. These include official speed limits, recommended speeds, information on road types and topography and real time traffic information. A mix from these different data is processed to enhance the algorithm.

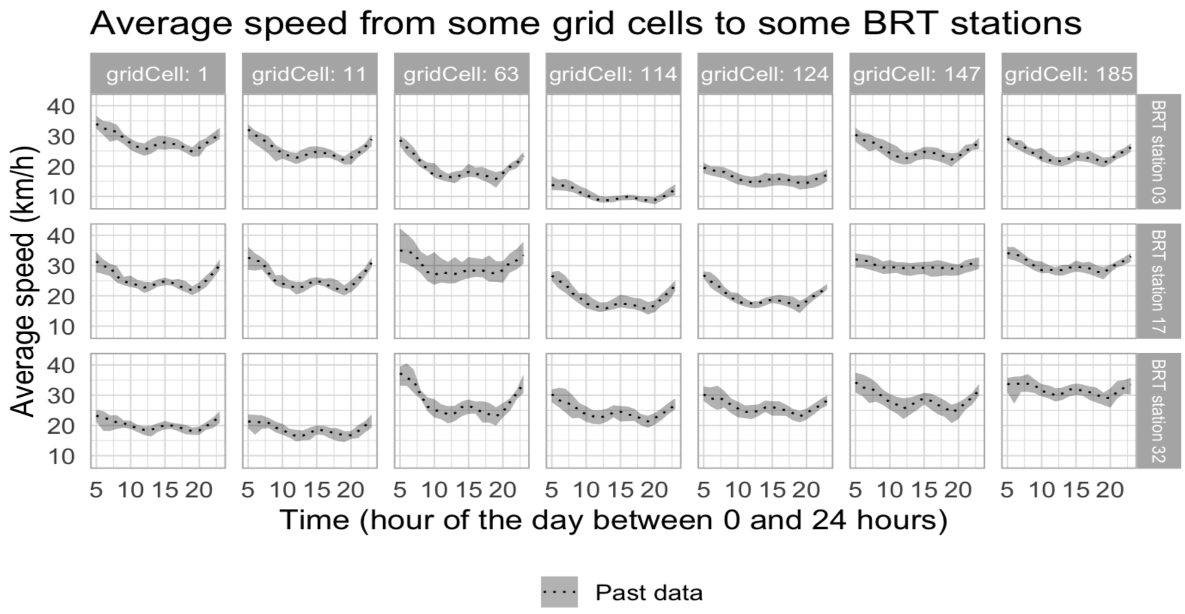

Figure 2-3: Average speed by time of day and route. 95% confidence interval in grey

2.4 Results

Results are presented in four sections. First, Google Maps® travel times estimate data is used to identify key attributes of the transport network, including hourly and weekly traffic variation across the city. Second, we investigate the effect of the new BRT project on vehicle travel times. Third, we assess how the Google Maps® data during a flooding event on June 4th 2018 to compare Fourth, we compare Google travel estimate data with a simple model of travel times in the city to assess the extent that Google travel data is providing 'additional value' beyond more basic modelling approaches, and the extent that biases may be present in the data.

2.4.1 Traffic variation in Huballi-Dharwad

Figure 3 shows average travel speeds between grid cells and BRT stations estimated using the travel times estimates from Google and the trip distance provided by Google. Results show a similar pattern over time, with congestion slowing travel speeds between 9am and 2pm (approximately) and then again between 5pm and 9pm (approximately). However, the degree of congestion (the change in speed) and the speed under low congestion, are found to depend significantly on factors specific to different routes.

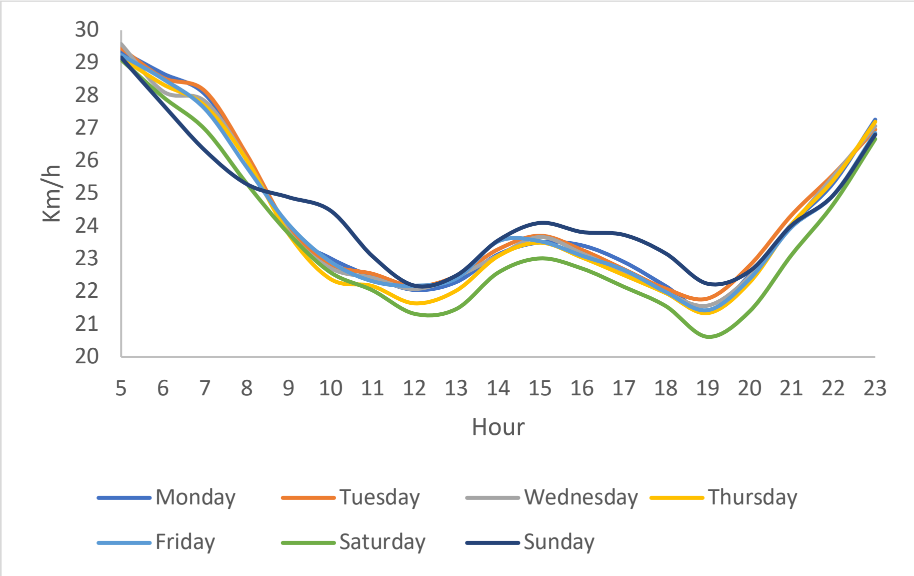

Figure 2-4: Average speed by time of day and week

In Figure 4 the morning and evening congestion periods are presented more clearly by assessing travel speeds across different routes. Combining these by day of week reveals that Saturday has the most traffic and Sunday has the least traffic congestion. The effect of time of day is seen to be significantly more important than the day of the week for the level of congestion given the much larger differences in travel speeds

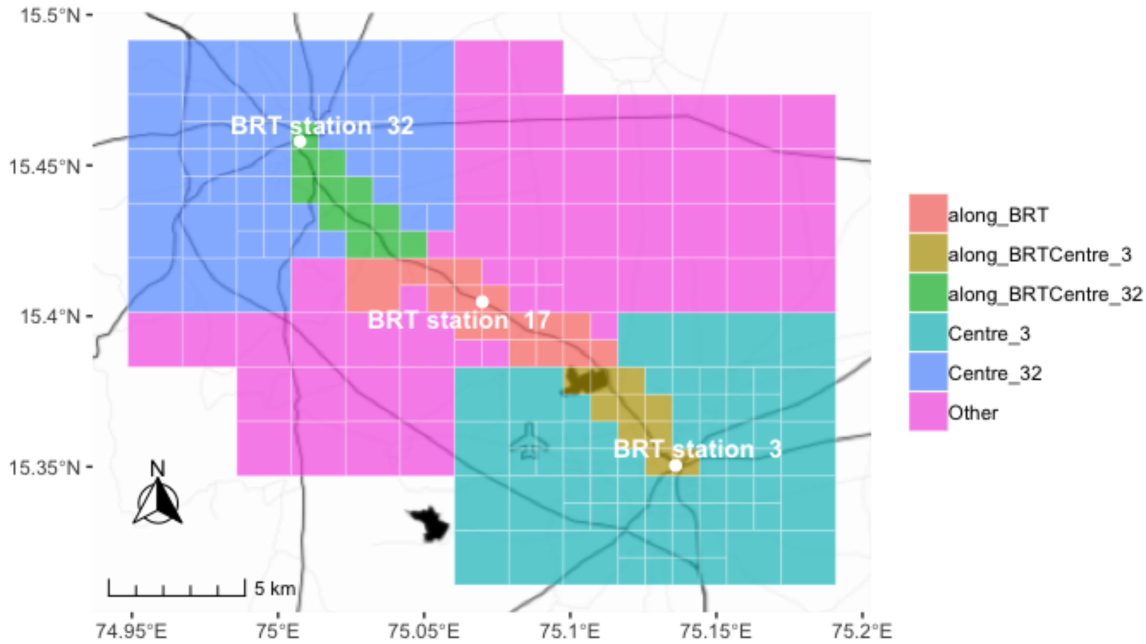

Figure 2-5: Zones of the city used to establish the impact of the BRT

2.4.2 The impact of the bus-rapid transport network

In order to understand the effect of the BRT we assess travel times before and after the BRT and compare routes that are parallel to and perpendicular with the BRT. The hypothesis behind this approach is that trips parallel to (or along) the BRT line will be affected by the new transport option, while trips perpendicular to the BRT should not be affected. To provide clarity the city is divided into regions, as shown in Figure 5.

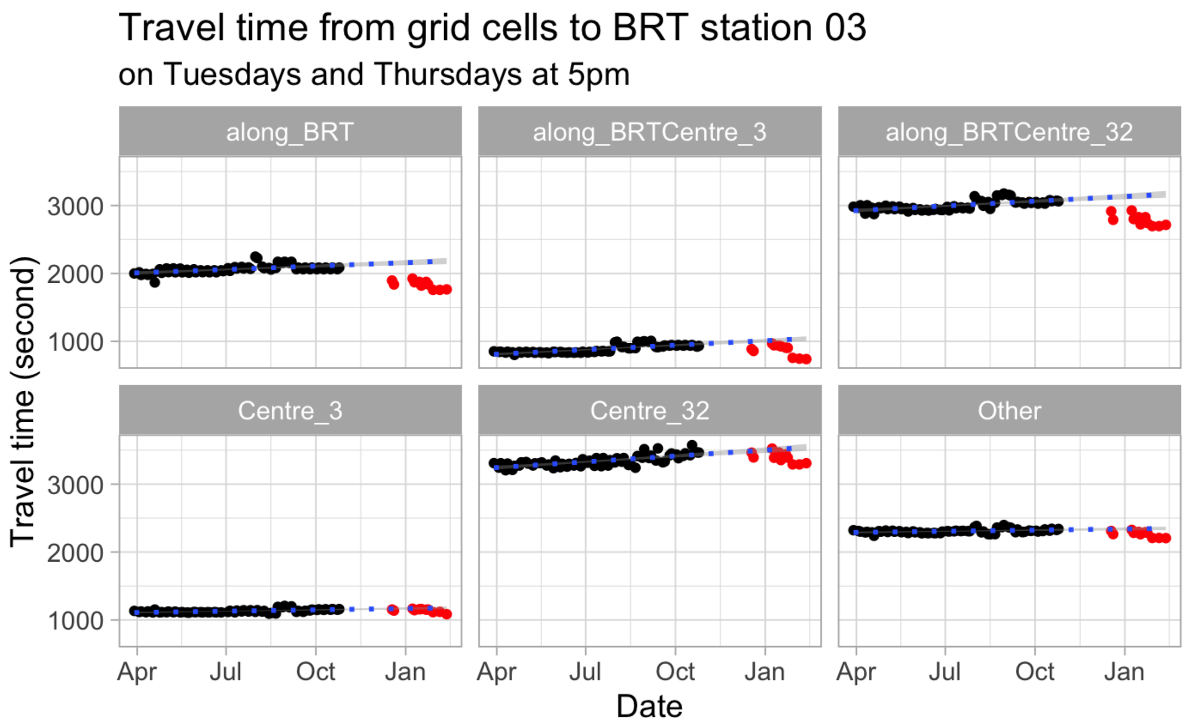

Figure 2-6: Travel times from grid cells to BRT station 03. Please note, the new BRT offers the most direct route from 'Centre 32' to station 3.

Figures 6, 7 and 8 show the change in travel times before (blue dots) and after (red dots) the BRT. Results show a statistically significant (at the 5% level), but small, change in travel times for most routes parallel to the BRT. Please note, those trips parallel to the BRT include all trips represented on the top row of each figure, labelled 'along', as well as some of the routes in the second row. Routes not parallel to the BRT, by contrast, do not show a consistent change in travel times comparing results before and after the BRT implementation. These findings suggest that in the immediate weeks and months after the implementation of the BRT the new bus has had the effect of improving congestion, one of the stated goals of the project. However, whether this effect is by moving drivers from cars onto the bus, by discouraging drivers from taking this route, or by another means is beyond the scope of this analysis to determine. Further, who is taking the BRT and how the specific trips they are taking have been affected is information not available using this data set and approach.

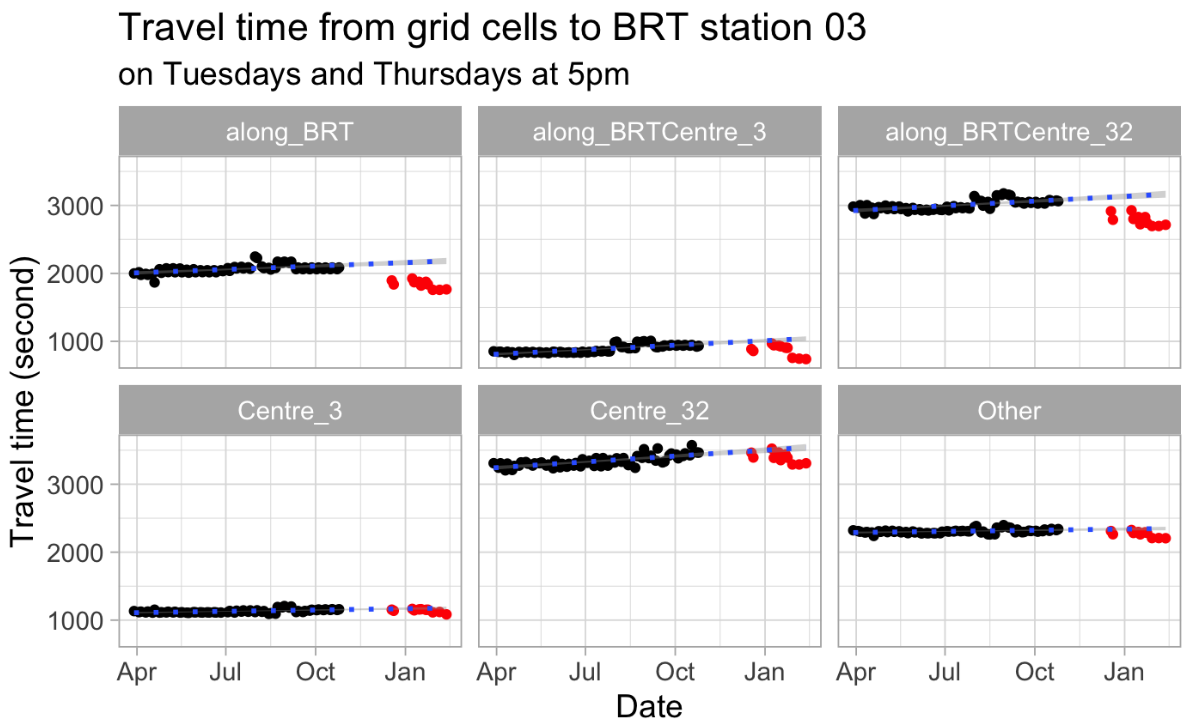

Figure 2-7: Travel times from grid cells to BRT station 03. Please note, the route along the new BRT offers to most direct route from 'Centre 32' to station 3.

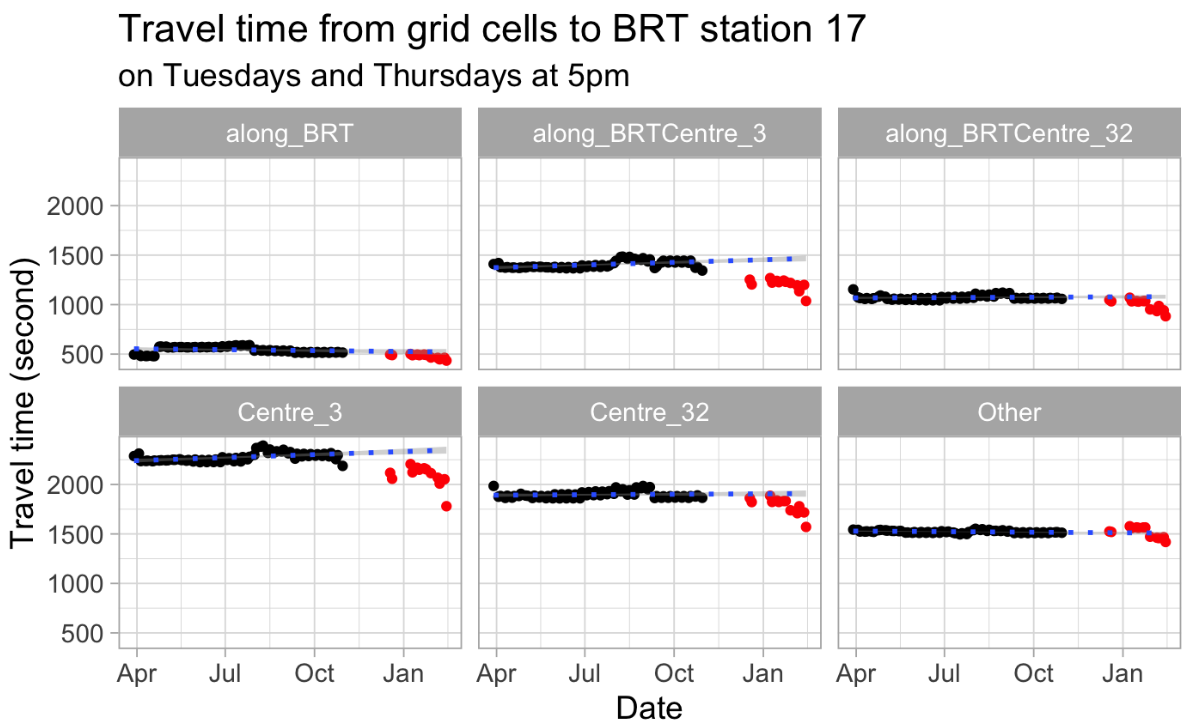

Figure 2-8: Travel times from grid cells to BRT station 17. Please note, along the BRT route offers to most direct route from both 'Centre 3' and 'Centre 32' to BRT station 17.

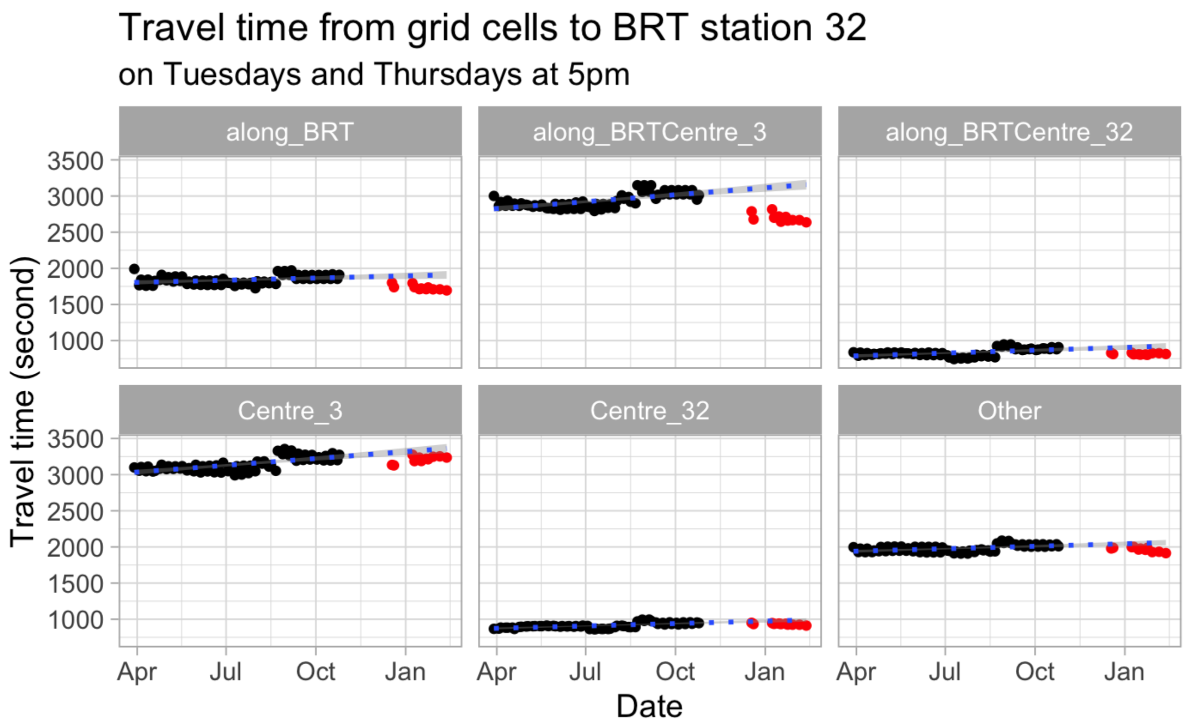

Figure 2-9: Travel time from grid cells to BRT station 32. Please note, along the BRT route offers the most direct route from Centre_3 to BRT station 32.

2.4.3 2.3.4 'Real-time' traffic analysis

One of the key advantages of having access to Big Data is its ability to rapidly provide information for users. To assess whether Google Maps® transport data could inform transport policy making in acute situations we look at data from June 4th 2018, a day of heavy rain and flooding in Huballi-Dharwad that followed on several previous days of heavy rain and flooding in the region (Times of India, 2018).

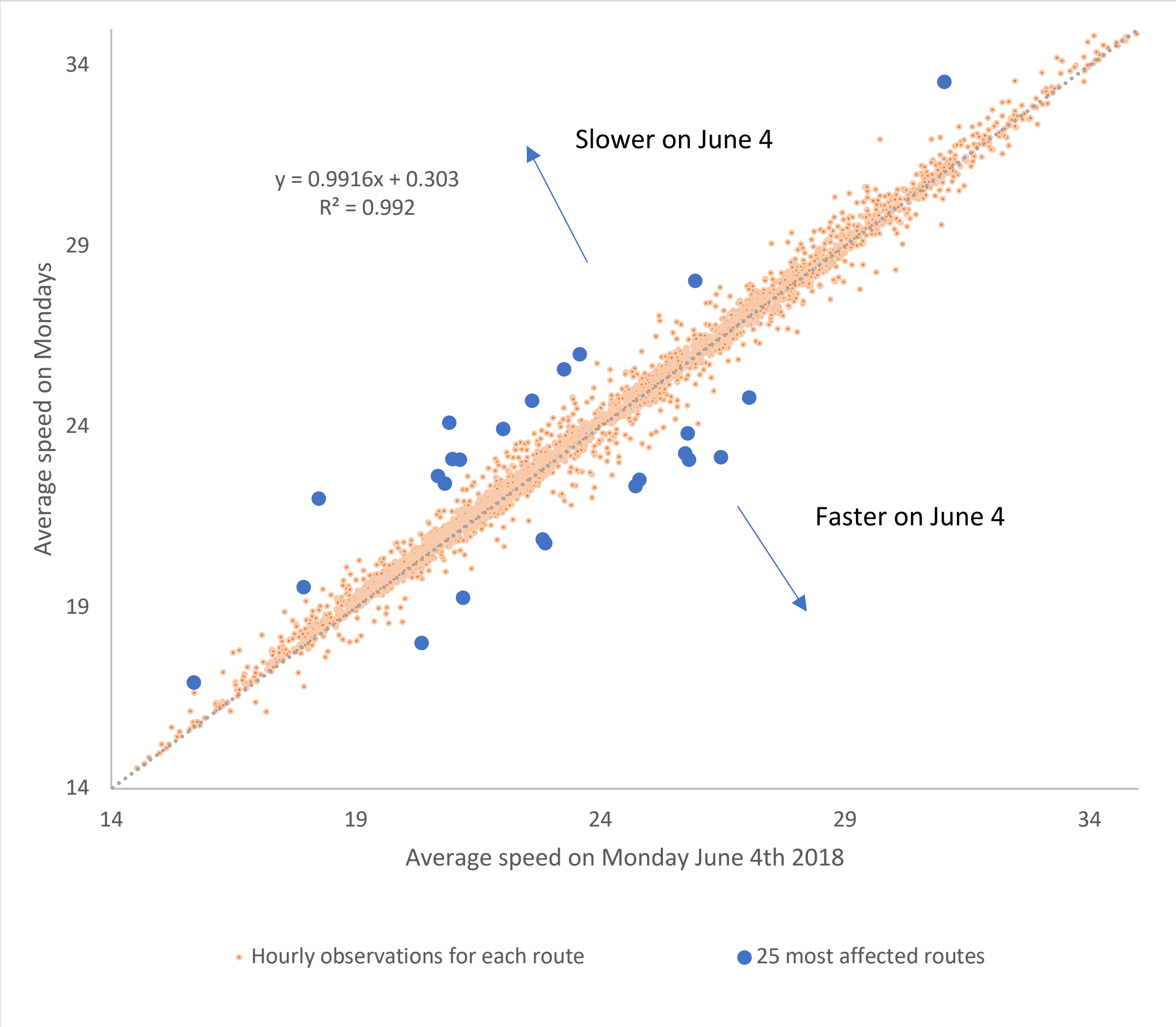

Figure 2-10: Speed for each hour-route combination on an average Monday and on Monday June 4th.

Figure 10 shows combinations of travel times on Monday June 4th 2018 on different routes at different times of day, and the average speed for that route at that time of day on Mondays (excluding June 4th 2018), across the dataset. Despite major flooding, results suggest that travel speeds across the city on Monday June 4th 2018 were very similar to travel speeds on a typical Monday and not significantly different at the 5% level. Similarly, there is little evidence of disruption to any specific routes. Of the 25 observations that showed the largest impact (each observation is one data point, representing an estimation of the travel time and distance between a cell and a centre or a centre and a cell), 14 showed faster times on June 4th and 9 showed slower times. Of these, only 5 routes were 10% faster or slower than usual.

2.4.4 2.3.5 Comparing Google Maps® estimates with a simple transport model

Following the results in the previous section we were curious to explore the extent to which Google data is adding on-the-ground information to its estimates. In the absence of detailed information on the way Google Maps® estimates are calculated, we develop a model of travel times that is based on a set of characteristics seen to have an important role in predicting travel times: the hour of the day, the day of the week, population density and the distance of the trip. Using linear-regression this model explains 85% of the variation across all 3.2 million trips in our dataset, suggesting that 15% of the variation in Google's estimated travel times is related to other factors. We assume that a significant portion of this 15% of addition variation comes from Google's ability to collect real-time travel information on actual travel conditions, relating for example, to the weather, traffic accidents, or other events that are too rare or uncertain to be included in the characteristics of our model.

The extent Google is able to capture this real-time information may not be the same across the city, particularly in slum areas due to a lower concentration of mobile devices. To test this hypothesis, we can compare the fit of our model for trips starting from slum areas versus the fit of our model for trip starting from non-slum areas.

If a subset of the dataset (slum or non-slum originating trips) shows a lower R^2 in our model, this suggests that Google might have more real-time information, allowing Google to provide more bespoke travel time estimates that differ from the ones in the 'basic model'. If the R^2 is higher this suggests Google travel time estimates are more likely to be based on a set of characteristics similar to those in our model, implying that they may not have more information to improve their estimates. This effect should be magnified for shorter trips: Longer trips will frequently converge onto the same routes and over the course of a longer trip drivers will have more opportunity to change their route to avoid traffic. We would therefore expect the R^2 to be higher for relatively longer trips compared with shorter trips.

Table 2-1: Adjusted R2 for models applied to data from grid cells (regions of the city) with the highest proportion of slum dwellers and from the remainder for the city. Number of observations does not apply for the model specification that includes only 1km by 1

	Model	**trip distance (km)**			
		<2 (n=86,559)	**<5 (n=505,702)**	**<10 (no=1,149,861)**	**<15 (n=1,956,916)**
90% of grid cells with the lowest proportion of slum dwellers	Distance	32%	60%	68%	78%
	Distance and density	43%	64%	69%	78%
	Distance and density and hour dummies	53%	71%	74%	83%
	Distance and density and hour dummies and day dummies	53%	71%	75%	83%
	Distance and density and hour dummies and day dummies and restricted to '1km by 1km cells	53%	72%	75%	87%
		<2 (n=2,810)	**<5 (n=35,505)**	**<10 (n=95,023)**	**<15 (n=170,615)**
10% of grid cells with the highest proportion of slum dwellers	Distance	26%	69%	66%	75%
	Distance and density	26%	72%	66%	76%
	Distance and density and hour dummies	85%	87%	74%	82%

	Distance and density and hour dummies and day dummies	87%	87%	75%	82%
	Distance and density and hour dummies and day dummies and restricted to 1km by 1km cells	87%	87%	79%	89%

Results find that the model of travel times we apply explains a higher proportion of all variation in trip times from slum areas compared with the remaining grid cells. This phenomenon exists across all grid cells and also when we restrict our analysis to the 'finer' 1km square cells. Results also show a higher R^2 as the minimum trip length is increased, in line with our assumption about longer trips.

These findings could be a result of fundamental aspects of transport in Huballi-Dharwad. Travel times from slum areas may be more predictable due to geography or the configuration of the travel network. This would be despite the fact that slum areas are found across Huballi-Dharwad including adjacent to non-slum areas. However, without detailed information on the raw data Google Maps® is using, or the way that data is processed before it is passed through Google Maps®, we cannot rule out that the data we are being provided with is more detailed outside of slum areas.

2.4.5 Discussion

From the perspective of a policy maker in Huballi-Dharwad (or another developed or developing urban area), the analysis presented demonstrates what appear to be some clear benefits of using Google Maps® data to inform the evaluation of transport policies, plans and programmes. Compared with surveys, traffic counts and other traditional methods of data collection, Google Maps® makes it relatively easy to collect large quantities of data in a timely fashion across the entire timeline of a project, irrespective of weather, holidays, or other unforeseen issues.

Moreover, this data can be used in ways that have clear policymaking value. Information on travel times by time of day and day of week can inform public transport scheduling, road maintenance and public works, and long-term urban development planning. This kind of research is foundational for urban transport policymaking and planning, but the challenge of collecting data and building bespoke models is a barrier in both wealthy and developing contexts alike.

Analysis of the BRT suggests Google Maps® data may also be able support ex-post assessment, a process that is critical for processes of learning but often not undertaken due to the cost and challenge of accessing data (Nicolaisen and Driscoll 2014). Results here, which show a relatively modest change in travel times along the BRT compared with routes perpendicular to the BRT, highlight the value of the large datasets accessible with Google Maps®, which allow for a level of statistical robustness that would be challenging with other methods.

Adding to the value of the above, a transport department that completed these analyses could easily replicate them in the future. And since policymakers in other urban areas also using Google Maps® would have access to data of the same types and format, knowledge sharing and learning could be radically increased. These realisations have enchanted academics who forecast the beginning of a fundamental shift in our epistemological approach to transport planning led by data analysis rather than the development of hypotheses (Kitchin 2014a; Rabari and Storper 2015), a notion that may be at odds with the scientific method.

The extent that such a shift in the nature of urban transport and urban transport policymaking is on the horizon is beyond the scope of this paper. However, the third and fourth analyses in the results section were undertaken with the intention of exploring how Google Data might contribute to more 'novel' analysis of the kind that has been associated with this transition (c.f Kitchin 2014b).

The speed with which data can be collected and assessed is a key feature of Big Data and has clear value for transport policymakers. Rapid analysis can help for identifying transport hotspots and for responding to emergencies. In contrast with our personal experience with Google Maps® in other urban contexts during periods of disruption, however, we were surprised to find no clear impact of the flooding in Huballi and the surrounding region on Monday June 4th 2018 in the data[2]. This finding is not only suspicious but alarming: Google Maps® is widely used by residents in the area and could therefore have encouraged potentially dangerous travel decisions. It also raises concerns about the veracity of the earlier findings of this analysis: data varies by time of day, day of week and distance, but to what extent is the data based on on-the-ground information?

The data provided by Google comes without any information on how it was put together. However, based on the limited information available about Google Maps®' algorithm, we can assume that travel time estimates are derived from both 'real' data collected from travellers with Android and Google devices, and from a model of urban transport used to make estimates in the absence of information from connected devices. The factors in this model may include trip distances, topography, and the time of day, among other factors.

In order to probe the characteristics of this underlying algorithm, we developed a simple model of the transport network. Across the entire dataset results show that characteristics including time of day, day of the week, the distance of a trip and the density of the urban area travelled through describe 85% of the variation in travel times. This suggests that either these variables, or factors correlated with them, are constituents of the model used by Google. This also suggests that 15% of the variation in estimated travel times may be attributable to other variables or information captured by Google connected devices. Wider factors might include topography, road quality and speed limits, while information collected from connected devices might include traffic caused by a car breaking down, a slow driver, or weather.

In this context, we would assume that data captured by Google connected devices would 'override' the estimates of the model. Described another way, if Google has information that a road is poor quality, on a steep hill and that it is the busiest day of the week and time of the day (implying that a road is likely to be relatively slow for vehicles according to the model), but connected devices are reporting that vehicles are travelling quickly, we would assume that Google would eventually conclude that this is a relatively fast route for cars and provide estimates accordingly. Similarly, for the opposite case, data from connected devices should allow Google to correctly predict slower travel times on roads even if an ex-ante estimate suggested relatively fast travel speeds. Over a long period of time, during which many data points are collected, Google estimates should improve significantly by this means.

Importantly, the extent to which Google can account for certain unpredictable events (for example a car breaking down) will likely still depend on timely data from connected devices. All else constant, this factor will be most prominent for shorter trips where there are fewer opportunities for alternative routes to avoid such events. We would therefore expect that the difference between a basic model of the transport network and a more complicated (and, by assumption, more accurate) model, such as that used by Google, would be largest for shorter trips and smallest for longer trips.

The failure of the just mentioned hypothesis for trips starting from slum areas, with the model we have developed providing a similar degree of accuracy for shorter and longer trips, may be explained in three (non-exclusive) ways. First, as with any statistical analysis, there is the potential that these results are a statistical artefact. This is mitigated by the number of observations and by the different specifications of the model presented. Second, the elements of the basic model may be a better fit for trips from slums over shorter distances. In other words, characteristics left out of our model, including topography, weather and car accidents may only have a small effect on travel times from slum areas. This seems unlikely as the slums are in different parts of the city and adjacent in many cases to wealthier areas (see Figure 2). Further, one would not expect some of these factors (a car breaking down or an unexpected rainstorm) to be significantly correlated with the wealth of the neighbourhood a car is passing through.

Finally, Google travel times from the slum areas of the city may not include the same amount and quality of on-the-ground data as they are able to access from wealthier areas, forcing Google to provide less accurate estimates. We would emphasise that these results call for further research to be verified. However, there is reason to think the third of these explanations could be the cause of these results. Only approximately one-third of the population has a smartphone in

[2] During the preceding 3 days and continuing through Monday night the wider area and Huballi-Dharwad received several meters of rain. Flooding during this period made it one of the most severe monsoon seasons on record (Times of India, 2018).

India in 2019 (Statista 2019). The vast majority of these devices are Android, but ownership is skewed towards the wealthier population (ibid). And among the poorer population, some share a device or leave it at home for safety purposes, further reducing their visibility in data collected. These facts suggest that there is a causal pathway leading to lower quality travel time estimates from poorer areas

While concerns around systematic biases in Big Data sets are well established (Kwan 2018; Batty et al 2012), a number of authors have implicitly made the assumption that these biases are not large enough to be a concern in analyses of Google data. In addition, the exact nature of these biases remains poorly explored. Here we find some evidence to suggest the existence of spatial and temporal limitations of Google data which may have a social consequence: reduced quality of travel time data for slum populations.

It should be noted that on-the-ground assessment to confirm these findings, or comparison with a city-based transport model, were not possible. Nonetheless, these latter analyses raise wider concerns about the use of Big Data for informing urban policies, plans and programmes: If there is not transparency around the quality of data and the way it has been processed there may be significant limits to the extent that 'surprising' results can be explained, leading to concerns about datasets as a whole. This issue is particularly evident in our findings around the days Huballi faced flooding but apply also to the findings on the differences between slums and non-slums, and the impact of the BRT. And since the data available is 'wide but thin', massive in the quantity of information but lacking in number of variables, corroborating the results with other datasets is challenging.

Important in this context is that the potential for errors in the data is known, but the nature of these errors is not. This is in contrast with conventional transport modelling methods, where the exact nature of errors is not known, but where statistical methods and comparisons with other datasets can be used to determine confidence levels and provide indications of biases. Big Data sources rarely come with a detailed methodology, quality assurance, or user manual of any kind. On the contrary, Big Data is often described as speaking 'for itself' (Anderson 2017; Villanueva et al. 2016). But if the data is of questionable validity – and therefore does not speak for itself – there may be some irony in using it for ex-post analysis.

For policymakers, the key concern in this context regards unintended consequences. An individual's travel app that does not work during poor weather may lead to a dangerous travel decision, but more likely leads only to a lengthy commute. A transport planner basing a policy or project on data that only considers fair weather, by contrast, may lead to a city gridlocked for the course of the monsoon. For the academic community the consequences may not be as immediate, but the 'intellectual debt' built from using data we do not fully understand can also lead to costs.

Addressing this challenge could be as simple as making the algorithms and raw data behind Google Maps® and other Big Data sources freely available. Assuming this may not be realised, firms could provide basic information around the inputs into their algorithms, indications of when outputs are estimated versus when they are based on collected data, and confidence levels/indications, so that users may be alerted to potential problems.

More generally, however, a deeper challenge faces policymakers and academics exploring the value of Big Data. While urban data and methods are sure to improve, subtle, and not so subtle, aspects of urban life will continue to fall between the columns of ever more impressive datasets. Can and should culture or values be modelled? And to the extent that they can, what roles and responsibilities for each of the agents who create, collect, store, manage, present and interpret that data? Those who view urban policymaking as a science and those who view urban policymaking as an art are unlikely to agree.

Reflecting on waves of enthusiasm for more 'scientific' approaches to urban planning over recent decades Duminy and Parnell (2020) remind us that the debates between 'interpretivists' and 'positivists' are old, well defined, and possibly growing more acrimonious. A practical path forward may lie with efforts to emphasise the value in different ways of generating urban knowledge. Big Data provides increasing rapid and analytically robust means of addressing specific questions. The robustness of the framing of those questions, and whether results hold wider significance, however, may be better informed by a wider plurality of urban methods and approaches, including the citizen science movements (Callaghan et al 2019), citizens assemblies (Stark et al 2020), urban labs (Nesti 2018), participatory games (Angelidou and Psaltoglou 2019) and a burgeoning set of wider methods that are being applied in a growing number of urban areas.

2.4.6 Conclusions

Google Maps® and other sources of Big Data present an emerging opportunity for policymaking in transport and more widely. The extent to which these approaches can be relied upon, however, depends on the value they add to analysis weighed against the new limitations and sources of uncertainty they generate. To date, quantitative analysis has placed much greater focus on the opportunities. Here, we contribute to what we hope will be a growing field of analysis assessing the quantitative shortcomings of Big Data approaches for informing policymaking, and how these may be overcome where efforts are made to understand the lived realities behind the data, and the complementarities between Big Data and and wider methods of knowledge generation in urban areas.

Future analysis in this field can be targeted to three areas. First, analysis can explore the existence and extent of disparities between the value of Big Data for populations from different socio-economic backgrounds. This analysis is essential to understand the extent and possible consequences for sustainable development, especially in rapidly growing urban areas where the vast majority of infrastructure is yet to be built. Second, analysis is needed to "truth" the proliferation of Big Data sources with on-the-ground realities. This can help to determine the key areas new data sources have shortcomings and advantages relative to established sources of information and methods of analysis. Finally, interdisciplinary work that explores, both conceptually and in practical terms, the ways empirical and qualitative urban data sources can be integrated is needed to ensure wider methods of knowledge generation in urban areas can complement the growing proliferation of Big Data.

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3 Data Scaling: Implications for Climate Action and Governance in the UK

Abstract

Local actors have growing prominence in climate governance but key capacities and powers remain with national policymakers. Coordination between national and local climate action is therefore of increasing importance. Underappreciated in existing academic and policy literature, coordination between actors at different scales can be affected not only by politics and institutional arrangements, but also by methods of data analysis. Exploring two datasets of GHG emissions by local area in England – one of consumption-based emissions and the other of territorial emissions - this paper shows the potential for a data scaling problem known as the modifiable areal unit problem and its possible consequences for the efficacy and equity implications of climate action. While this analysis is conceptual and does not identify specific instances of the modifiable areal unit problem or its consequences, it calls attention to methods of data analysis as possible contributors to climate governance challenges. Among other areas, future analysis is needed to explore how data scaling and other aspects of data processing and analysis may affect our understanding of non-state actors' contribution to climate action.

Sudmant, Andrew

3.1 Introduction

The growing number and diversity of actors playing a role in the fight against climate change is widely recognised as a positive development for the climate movement. A greater diversity of actors is suggested to lead to more dynamic and innovative approaches to governance (Jordan et al., 2015). Devolution and depoliticization of responsibility for action has the potential to support more effective decision-making (Romero-Lankao et al., 2018). The bringing of stakeholders and citizens closer to the decision making processes is seen to increase the democratic legitimacy of climate actions (Cattino & Reckien, 2021). And higher levels of engagement facilitated by polycentric governance can help to build a social mandate for action (Howarth et al., 2020). Evaluating the climate action commitments of actors including local governments, schools, universities, communities and individuals is a growing area of research (Grafakos et al., 2020; Messori et al., 2020).

A growing number and diversity of actors can also, however, increase the challenge of coordinating action, potentially leading to duplication of effort, mixed signals to households and businesses, and conflicting climate actions (Biermann, 2014; Bulkeley, 2010; Li & Shapiro, 2020). Understanding how the growing involvement of non-state and sub-national actors is affecting climate action requires detailed policy and place specific analysis, and the continued developed of theory (Bulkeley, 2010; Bulkeley and Betsill, 2005; Gouldson et al., 2016; Howarth et al., 2020; Willis et al., 2022; Creutzig et al 2024). Missing from existing analysis, however, is consideration of the way methods of data analysis, independent from institutional arrangements and mobilisations of power, can affect actor's understanding of the climate challenge.

Using datasets of GHG emissions at the local level in the UK, this analysis provides conceptual insight into the way methods of data analysis can affect climate action by demonstrating the potential for the modifiable areal unit problem. The modifiable areal unit problem has been highlighted as affecting our understanding of the impact of climate change on agriculture (Cai, 2021; Deschênes & Greenstone, 2007) and in the context of adaptation and climate resilience (Hutton et al., 2011). To the knowledge of the author, however, research has not considered how the modifiable areal unit problem applies to climate change mitigation.

Analysis focuses on the UK due to the unique conditions of climate governance that have developed over the last decade in the country. At the local level, efforts to develop and nurture local, and so-called 'place-based', climate actions have surged over recent years in the UK. Since 2019, 314 (of 408) local authorities have declared Climate Emergencies, 16 local authorities have developed Climate Commissions (place-based non-government bodies responsible for supporting local climate action), and 210 local authorities have established net-zero targets for decarbonisation before the 2050 date set out in national legislation.

In Section 2 we outline our approach, including how we model the modifiable-areal-unit problem and the way we explore how the modifiable-areal-unit problem might have consequences for the efficacy and equity implications of climate action. Following this, in Section 3 we present the methodology. In Section 4 we explore how the modifiable-areal-unit problem may lead to conflicting climate priorities between national and local actors in the UK. In Section 5 we discuss what the possible implications of the modifiable-area-unit problem for the efficacy for climate action and for the distribution of the costs and benefits of climate action. In Section 6 we reflect on the implications of this research for climate policy and the governance of climate change.

3.2 The Modifiable Areal Unit Problem and Climate Mitigation

The modifiable-areal-unit problem consists of two related issues. A scaling issue can occur when data is aggregated, for example, when moving from a local to a regional scale of analysis. At each stage of aggregation, characteristics that are unique to any local area can become harder to identify at higher level geographies. A zonation issue can emerge when data is aggregated into different configurations, for example the splitting of a region into electoral districts. In this analysis only the scale effect is considered. Hereafter we refer to the modifiable-area-unit problem as the 'data scaling problem'.

Figure 1 provides an example of a scale effect emerging via the modifiable areal unit problem. For each of local areas A, B and C, different sources of emissions (represented by icons that each represent one unit of GHG emissions) are of relatively greater and lesser importance. Local area A, for example, has no emissions from agriculture (represented by the cow), while agriculture is the largest source of emissions for local area C. Climate action plans for each local area would therefore be likely to focus on different sources of emissions. Local area A, for example, would be more likely to focus on housing, while C would be more likely to focus on agriculture. A climate plan focusing on the emission *across* these local areas, however, would be likely to view housing as its highest priority – since it is the largest source of emissions - followed by agriculture.

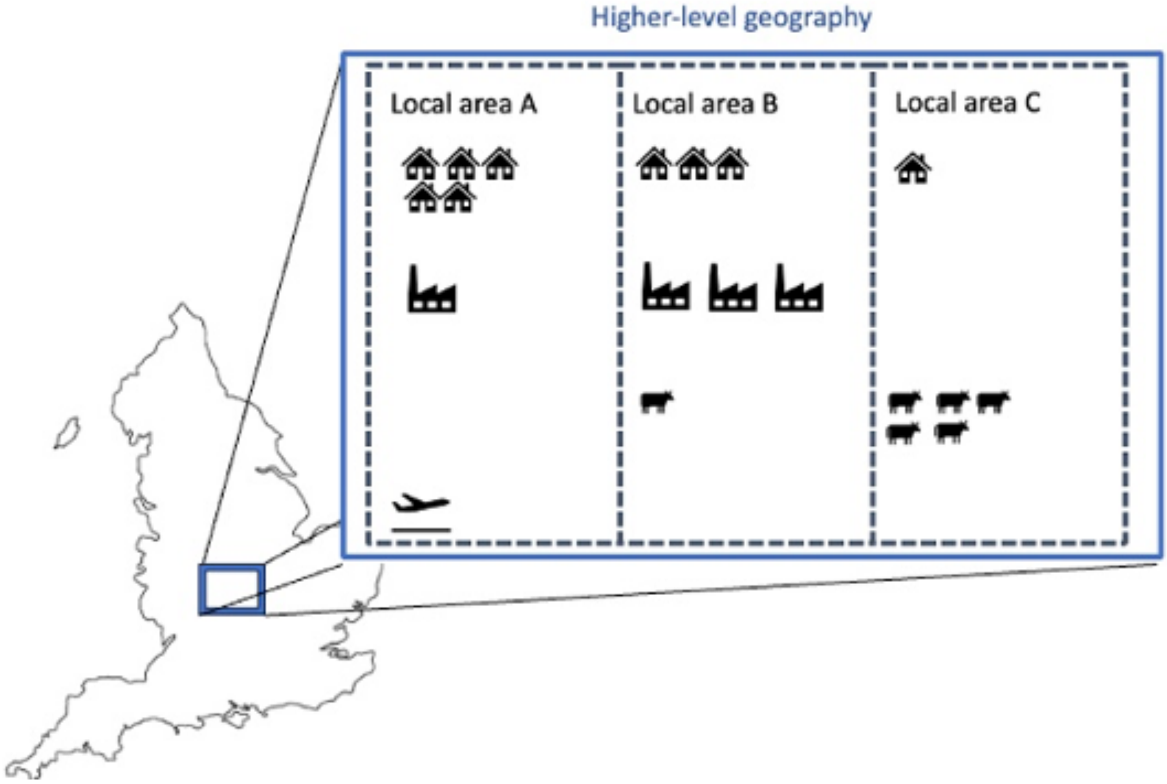

Figure 3-1: A simplified representation of the modifiable areal unit problem. Each icon represents a unit of emissions with different icons representing different sources of emissions in a region in England. The cow represents agriculture, the house represents the domestic sector, the airplane represents aviation, and the factory represents industry.

Different priorities for climate action within local areas compared with across local areas could lead to consequence for the effectiveness of climate action. If the climate action plans focused on a single priority area, a plan developed across local areas would address 9 units of emissions from the housing sector (5+3+1), while climate plans in each area would focus on 13 units of emissions (5+3+5). Individual climate plans could therefore lead to more effective climate action by generating more opportunities for intervention.

Different priorities for action between the local and higher-level geographies could also have equity implications. If climate actions are costly for households and businesses, the climate plan developed at the higher-level geography could impose more costs on area A than B or C due to the housing sector being relatively larger in area A. Conversely, if climate actions generate net benefits – because there are subsidies from government or through energy savings or the co-benefits of climate action – area A could benefit over areas B and C.

This example, and the approach taken in this paper, offer a hugely simplified representation of the way climate action plans are developed and of the possible efficacy and equity implications of these plans. Climate action plans at all levels are developed in the context of wider policies and priorities, existing plans, and the plans of wider actors, rather than a narrow focus on the scale of GHG emissions (Gouldson et al., 2020; Grafakos et al., 2020, Balouktsi, 2019; Dale et al., 2019; Howarth et al., 2021). The efficacy and equity implications of plans depend on factors that include the measures implemented (Millward-Hopkins et al., 2017), the sector considered (Mayrhofer & Gupta, 2016) the socio-economic context (Colenbrander et al., 2017) and the approach to implementation (Klenert et al., 2018).

Setting these considerations aside dramatically narrows the scope of conclusions that can be drawn from this analysis. In particular, analysis will not be able to identify specific instances of the modifiable areal unit problem or its consequences. Using real GHG data however, allows this analysis to investigate an underexplored question: how the methods applied during data analysis – even when the same data are used by different actors – may contribute to different perspectives on the climate challenge. Exploring this question expands our understanding of the factors affecting the governance of climate action.

3.3 Methodology

Two datasets are used in this analysis. The first consists of 32,844 emissions footprints from Lower Layer Super Outputs Areas (LSOAs) covering 12 sources of emissions. LSOAs are a geographic designation that includes an average population of 1500 people. This dataset was developed by the Centre for Research into Energy Demand Solutions (CRED) and is available from their place-based carbon calculator (CRED 2021). The second dataset consists of territorial emissions across 407 local authorities between 2005 and 2021 (BEIS 2023). Local authorities have an average population of approximately 165,000. Local authorities have responsibilities over planning and development, waste management, and key aspects of transport, making them key actors in climate action planning and delivery.

The dataset from BEIS contains territorial emissions, the accounting approach used by the UK at the national level and the accounting approach applied by most climate actors in the UK. The CRED dataset provides data to the LSOA level, providing insight into community-level mitigation planning. The CRED dataset is developed around consumption-based emissions footprints, an approach to emissions accounting that includes supply-chain emissions.

Each of these datasets have limitations. The CRED (2021) consumption-based dataset uses national data for estimating the emissions associated with some forms of consumption and downscales GHG data from the national level on a population basis. These necessary but simplifying steps, reduce the differences in emissions between areas, obscuring potential scaling issues. The dataset from BEIS (2023) are only to a local authority level and are reported with a 2-year lag. These limitations notwithstanding, using two different datasets and accounting approaches help to provide a more robust analysis of the potential for a data scaling problem.

The following equations are used in this analysis. To calculate GHG average per capita emissions for a given community:

$$GHG_j = \sum GHG_{i,j} \ / \ \sum p_i \qquad (1)$$

Where GHG_j is average per capita GHG emissions in sector j, $GHG_{i,j}$ is average GHG emissions of sector j in community i, and p_i is the population of community i. To sum across multiple communities as we move from a local to a regional or national geography $i \in n$ sums across the set of local communities in the higher-level geography:

$$GHG_{j,n} = \sum_{i \in n} GHG_{i,j} \ / \ \sum_{i \in n} p_i \qquad (2)$$

To understand how the scaling of emissions could affect climate action, analysis compares the share of total emissions covered when climate action plans are developed at different scales using different geographic aggregations of data.

Priority areas for climate action are determined based on the relative scale of sources of emissions where a sector with larger emissions is identified as a higher priority than a sector with lower emissions. As previously highlighted, this approach provides a simplified representation of the way priorities are set for climate action. The purpose of applying this simplified approach is to establish in a clear and transparent way the potential for methods of data analysis to effect approaches to climate action.

Net-zero climate targets are generally understood to require all sources of emissions to achieve near zero emissions in the near future, either through emissions mitigation measures or through a combination of mitigation measures and carbon removals (Peters, 2018). Climate actions plans at both the national and local level, however, frequently highlight specific sources of emissions in their near-term focus (cf Reckien et al., 2018). Consequently, the share of total emissions covered by a climate plan developed at a local level will not always be the same as the share covered by a plan developed at a higher geography.

Following the approach in Section 2, the potential efficacy implications of data scaling are explored through the share of emissions covered by different climate action plans, with a larger coverage of emissions assumed to be associated with a more effective climate action plan. In the example in Figure 1, for example, more emissions are covered when the single largest sector at each local geography is focused on, compared with focusing on the largest source of emissions across all geographies.

Similar to the approach in Section 2, the potential equity implications of data scaling are considered by comparing the share of total emissions covered between local level (LSOA) climate action plans. Looking across local areas more variation in the share of emissions to be covered by climate actions is interpreted as greater potential for equity implications from climate action. For example, if in one scenario some local areas are required to target 100% of their emissions and others target 0% of their emissions, the approach here determines that this would lead to a more unequal distribution of costs and benefits from climate action than if all local areas were required to address the same share of their emissions.

3.4 Results: The Effect of Data Scaling on Climate Action Priorities in England

To understand how the scaling of data could lead to different approaches to climate action we can explore how sources of emissions are seen to be larger and smaller at different scales of analysis. Figures 2 and 3 compare the rank of emissions sources at the lowest and highest geographies. Figure 2 investigates a dataset with 32,844 LSOAs and 12 sources of emissions while the Figure 3 investigates a dataset with 407 local authorities and 33 sources of emissions. A higher percentage (and darker cell) indicates that the national ranking of a sector is more frequently the same as the local ranking of a sector. For example, the cell in the bottom left of Figure 2 shows that 53% of the time the sector with the largest volume of emissions is the same at the national level and the LSOA level.

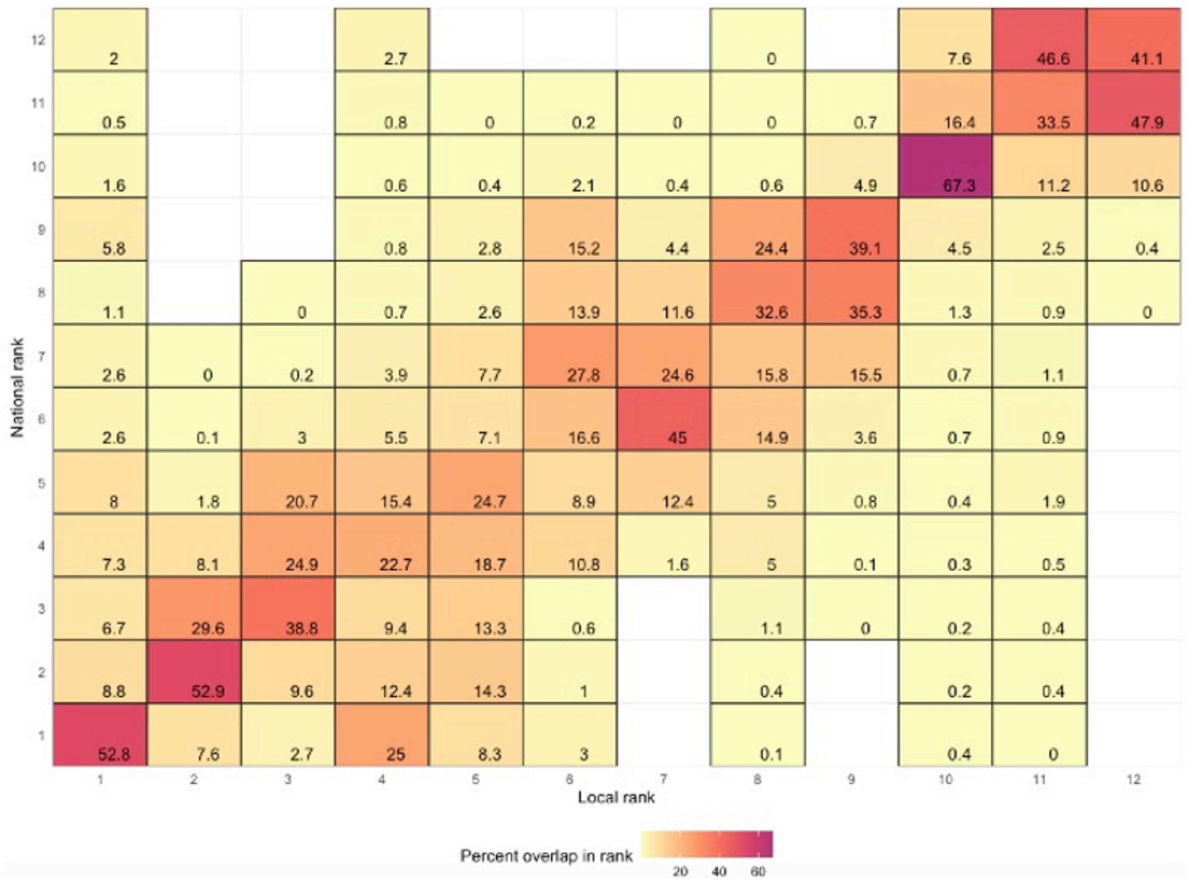

Figure 3-2: Rank of sources of emissions at the national versus LSOA level. Consumption-based emissions, 12 sources of emissions. CRED (2021)

These figures demonstrate that the ranking of emissions by sector is meaningfully affected by the geography used for analysis. In Figure 2 the largest source of emissions at the LSOA level is only among the largest three sources of emissions of the national level 68.3% of the time (52.8% + 8.8% + 6.7%). Similarly, in Figure 3 the largest source of emissions at the local authority level is only among the largest three sources of emissions of the national level 73.8% of the time (40.4%+ 22.2%+11.2%). This suggests that if climate action at the national level prioritised the three largest sources of emissions, for approximately 3 in 10 local areas the largest source of emissions would not be addressed.

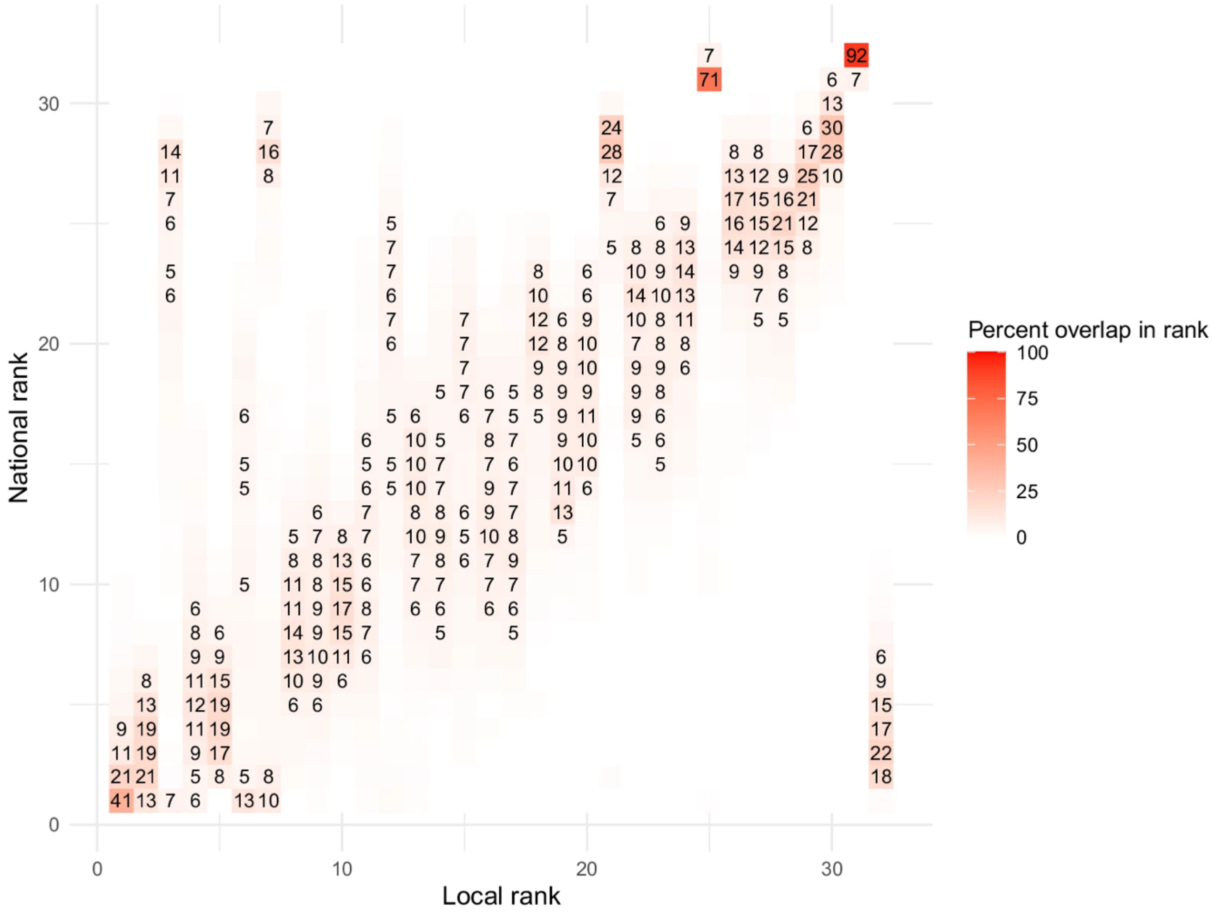

Figure 3-3: Rank of sources of emissions at the national versus local authority level. 33 sources of emissions, territorial emissions. BEIS 2023. For clarity values smaller than 5% have been removed.

Figures 2 and 3 shows how a national ranking of emissions by sector will be different from a local ranking. The degree to which this affects climate action, however, will depend on the size of sources of emissions and the number of sources of emissions included in a climate action plan.

Figures 4 and 5 compare the share of emissions covered by climate action plans derived from national (teal) or local (pink) prioritisation along the x-axis. Under national prioritisation (teal), all local areas address emissions from the same sources of emissions, with the set of sources of emissions that are prioritised determined by the ranking of sources of emissions by size at the national level. Under local prioritisation the largest sources of emissions specific to each local area are prioritised. The solid vertical lines show the average share of emissions covered by each approach. Along the y-axis are the number of sources of emissions included in a climate action plan.

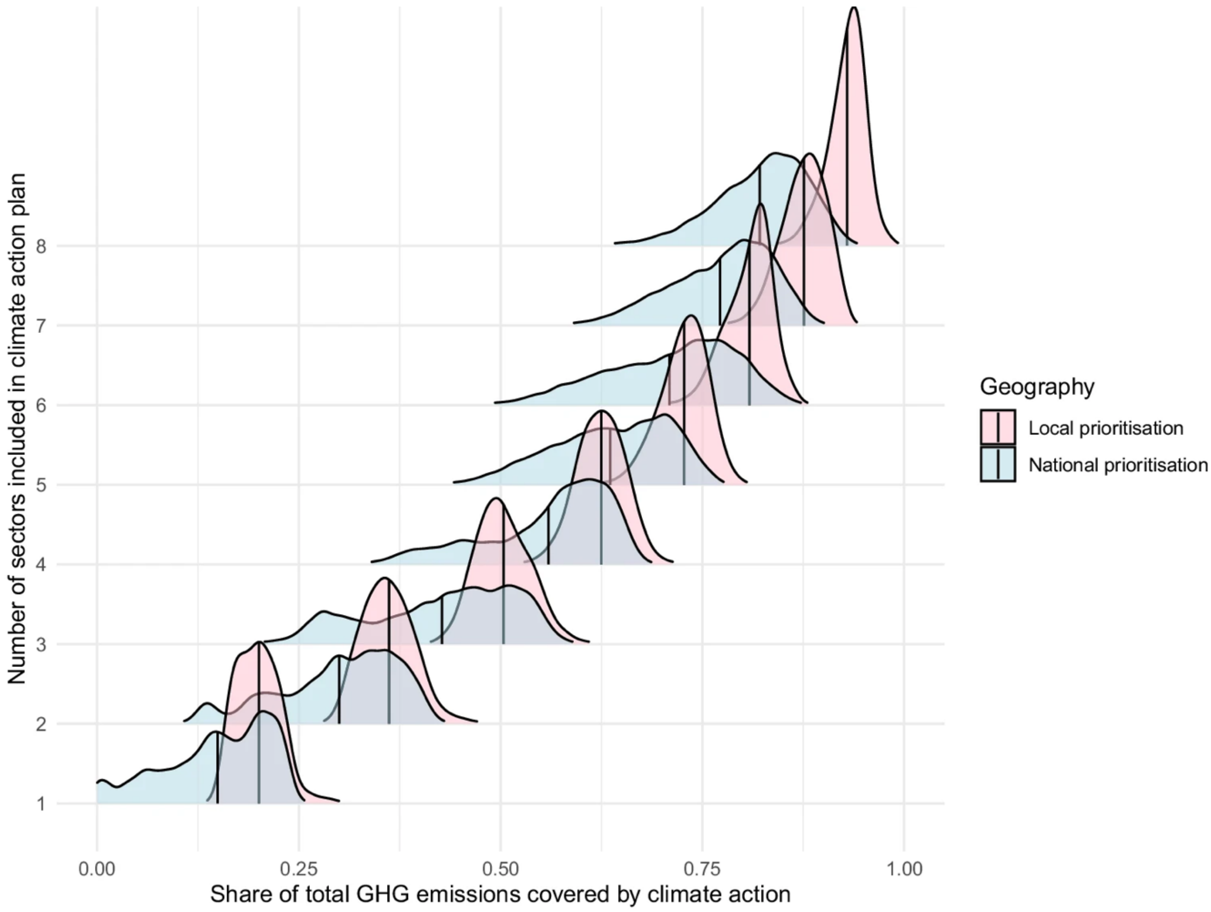

Figure 3-4: The density of LSOAs by the share of their emissions covered when local or national prioritisation guides action. The solid line shows the average. CRED data on consumption-based emissions. Local areas are LSOAs.

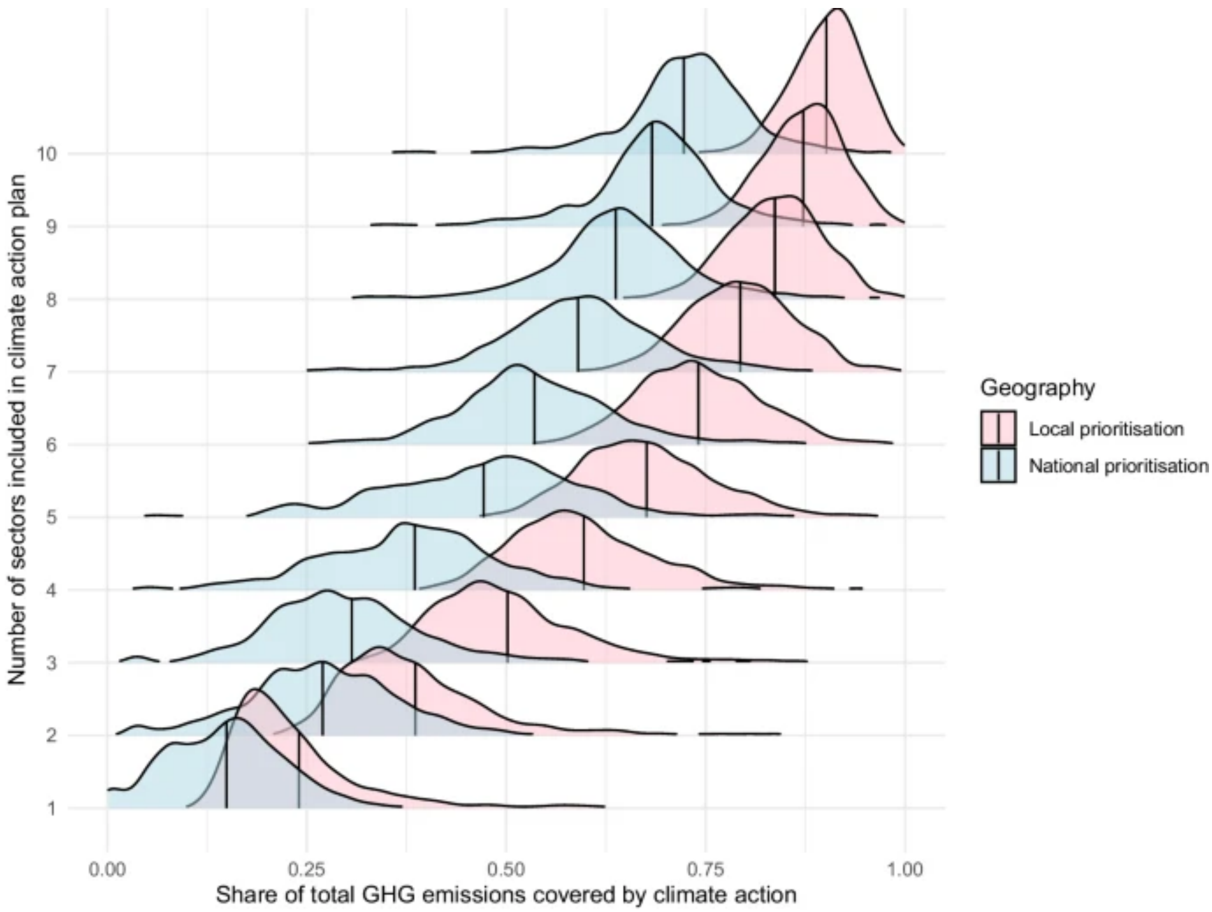

Figure 3-5: The density of LSOAs by the share of their emissions covered when local or national prioritisation guides action. The solid line shows the average. BEIS data on territorial-based emissions, 2005-2021. Local areas are local authorities.

Two insights can be drawn from Figures 4 and 5. First, while climate action plans developed from the sources of emissions largest in each local area cover a larger proportion of GHG emissions, the difference (identifiable by comparing the distance between the solid vertical blue and pink average lines in each distribution) diminishes as the number of sectors included increases. If three sources of emissions are considered, focusing on the priorities specific to each LSOA increases the coverage of a climate action plan by 28-35%. However, when half of emissions sources are covered by action, a coverage more similar to what is seen in typical climate action plans in the UK and internationally (c.f Colenbrander et al., 2019; Creutzig, 2015; Millward-Hopkins et al., 2017; Williamson et al., 2020), the difference diminishes to 12-16%. For a typical local area, climate plans developed using national sources of emissions will therefore cover similar volumes of emissions as climate actions plans developed using local sources of emissions in cases where a large share of emissions sources are considered.

Second, Figures 4 and 5 show that share of total emissions covered by a climate action plan varies more between local areas when national prioritisation is used in the place of local prioritisation. This can be seen in the long tail of the blue (national) distributions in Figures 4 and 5. Although the different in emissions coverage diminishes as more sectors are considered, for a subset of local areas the difference between national and local prioritisation stays quite large. Considering the case where half of all sources of emissions are considered, the LSOA in the 10th percentile for coverage of its emissions would be addressing 62-76% of its emissions if national priorities were applied versus 72-84% if local priorities determined the sources of emissions to be addressed. For the local areas in the 10th percentile moving to local priorities would therefore increase the coverage of climate action plans by 20-25%.

Locally specific prioritisation therefore significantly improves the coverage of climate action for a subset of LSOAs. Identifying these communities may be important to improve the efficacy of climate action if covering a greater volume of emissions leads to more opportunities for climate action. Identifying these communities may also be important from an equity standpoint: If climate actions are costly, these places may be addressing less than their fair share of emissions. If climate action carries benefits, on the other hand, either indirectly via cleaner air or job opportunities, or directly via investment and government subsidies, these places may be receiving less than their fair share.

To explore which places may be most affected by this problem Table 1 shows the correlation between the English index of multiple deprivation and difference in coverage of emissions between national and local climate action plans. The English Index of Multiple Deprivation is a composite index that includes factors relating to income, employment, education, health, crime, barriers to housing and services, and living environment.

Table 1 suggests that socio-economic status may be a strong predictor of the extent to which the national prioritisation of actions aligns with a local prioritisation. A higher index of multiple deprivation indicates more socioeconomic challenges. The positive correlation suggests that national and local climate action plans become more different as levels of deprivation increase. These results are statistically significant at the 1% level. These results do not provide any insight into a causative relationship.

Table 3-1: Pearson's Correlation Coefficient for the difference between

Socio-economic indicator	Correlation with the difference between local and national prioritisation for the CRED (2021) dataset	Correlation with the difference between local and national prioritisation for the BEIS (2023) dataset
Multiple index of deprivation	0.08	0.11

3.5 Discussion

3.5.1 Data Scaling and the Efficacy and Equity Implications of Climate Action

Priorities for climate action at the national level almost inevitably differ from priorities for climate action in local areas. In part these differences reflect the divisions of powers and capacities between different levels of government. Political and ideological positions, past and existing approaches to climate action, and socio-economic context, among other factors, also affect what climate actions are prioritised (Bulkeley & Betsill, 2005; Gouldson et al., 2014; Howarth & Parsons, 2021). Here we show that differences in the prioritisation of climate actions between local and national actors could also be affected by methods of data analysis. When 3 or fewer sources of emissions are prioritised for action, climate action plans developed at the local level could cover 35% more emissions than climate action plans developed at the national level as a consequence of data scaling. To the extent climate action plans are more effective when they are targeted towards larger sources of emissions, these results show that data scaling could in theory impact the effectiveness of climate action.

Prioritisation in this analysis was determined only by assessing the scale of emissions from different sources, setting aside other factors that influence priority setting. While further work is needed to understand how other factors might reduce or increase the effects of data scaling, we would cautiously suggest these factors could increase the effects of scaling. Socioeconomic context, for example, would likely increase variation between local areas, making it harder for any set of climate actions at the national level to align with the priorities of local areas.

The potential for impact on the equity of climate actions may be more significant than the effect on the efficacy of climate action. Recent analyses suggest that the transition to net zero emissions may generate net economic opportunity. Green investment can help to correct market failures such as those associated with fossil subsidies (Monasterolo & Raberto, 2019), and support innovation and long-term economic growth (Stern, 2015). Case studies and literature reviews find that both private financial returns (Colenbrander et al., 2016; A. Sudmant et al., 2016) and wider public benefits via cleaner air, reduced congestion and new employment (Dowling et al., 2022; Gouldson et al., 2018; Haines, 2017; Sudmant et al 2024), can substantially outweigh the financial costs of mitigation. Overwhelming these benefits, of course, are the value of impacts avoided from biodiversity loss (Pires et al., 2018), heat stress (Santamouris, 2020), reduced agriculture productivity (Ortiz-Bobea et al., 2021), desertification (Huang et al., 2020), and other impacts of climate change.

Accompanying the potential benefits climate action, however, are the need for reskilling millions of workers (Bowen and Kuralbayeva, 2018; Robins et al., 2019), the burden on the financial system of stranded assets (Mercure et al., 2018), the need to mobilise trillions in investment capital (Giglio et al., 2021), and the challenge of unlocking social and economic systems tied to fossil fuels (Ivanova et al., 2018). In many cases these costs may be concentrated in particular geographies, or for particular subsets of the population (Green & Gambhir, 2019). Challenging further the question of whether mitigation leads to net costs or benefits, different policy approaches will have different equity consequences with even small changes to policies sometimes leading to substantial changes in their socio-economic impacts (Gouldson et al., 2018; Klenert et al., 2018). And since low and zero carbon investments can generate path dependencies, especially where they are expressly designed to remake the economy (Gouldson et al., 2015b; Hepburn et al., 2020), welfare and distribution effects can compound over time, magnifying and perpetuating existing inequalities.

Uncertainty around the scale and nature of both the impacts of climate change and the actions we take to address climate change make climate equity and climate justice loom even larger for policymakers. Analysis here shows a mechanism for the geographic lens of climate policymaking to lead to variation in the levels of climate action between communities, potentially magnifying variation in the welfare consequences of action and adding to this challenge. Further, the effects consistently show a skewed impact: For any climate action plan that covers less than every source of emissions, a small number of local areas will face higher than average emissions mitigation while a larger number will face lower than average emissions reductions. A relationship between deprivation and the overlap between national and local climate action plans suggests places facing the highest levels of deprivation could face the most significant impacts from data scaling.

Potential for a scaling problem, however, is not the same as the existence of a scaling problem. Variation in the sources and scales of emissions and other characteristics between local areas create the conditions for a scaling problem, but these same factors are also the reason for flexible programs of action and the devolution of responsibilities for action. In section 5.2 we consider data scaling in the context of climate governance in the UK.

3.5.2 Data Scaling and the Governance of Climate Action

Regional and local actors in the UK have taken different approaches to climate governance compared with the national government. The national approach to climate action, characterised by a focus on specific sources of emissions, an expanding scope of action and rising targets, is an incremental approach to climate action. The climate targets set by local authorities, of which nearly half are for 2030, by contrast, demand dramatic near-term society-wide reductions in emissions – a transformative approach to climate action (Hurlimann et al., 2021). The national approach has been driven by market-based measures and regulatory interventions while local action has to date been driven by public-private partnerships, measures to enable the climate action of non-state actors and actions to address own-source emissions (Howarth & Parsons, 2021).

Even the arguments for action at each level, if not in opposition, present climate action from different perspectives. Climate action at the local and community level, often developed through place-based roadmaps (Gouldson et al., 2020) supported by programs of community engagement (Howarth et al 2021), and developed with narratives that position climate change around communities, cities, homes and the countryside (Howarth and Parsons, 2021), frequently make emotional appeals foundational to their case. By contrast, the national approach to climate action, with its basis in legal text and techno-economic modelling, makes logical appeals more central. A political and ideological divide thus separates local climate action in the UK and the national program of climate action.

This context is fertile ground for a scaling problem to affect climate action. Political and ideological differences stand in the way of the coordination and collaboration between actors at different scales while different approaches and narratives make the integration of climate action more challenging. Superficially it would also appear that national policy has been influenced by a scaling problem. Action to date has been focused on large sources of emissions while emissions from sectors that are smaller and that (in some cases) vary more dramatically between local areas has been lacking. The UK Climate Change Committee, for example, the independent organisation tasked with providing guidance to the UK government on climate change, has found that action on emissions from aviation, agriculture, heat and buildings has been lagging and continues to be undeveloped in existing plans (CCC 2021, 2023).

The extent, of course, that data scaling has directly affected national government policy in the UK likely to be limited. Institutional arrangements, political ideology, and the relative progress of decarbonisation technologies each likely play a much more significant role in the determination of national climate policy (Averchenkova et al., 2021;

Berglund and Bailey, 2023; Howarth et al., 2020; CCC 2023). Indirectly, however, analysis of data scaling contributes to our understanding of climate governance in the UK by emphasising the need for comprehensive and flexible climate action plans.

Comprehensive plans ensure the burdens and benefits that come from climate action are more evenly distributed across geographies. More comprehensive plans also support system-level interventions that are critical for the next stages of the transition (Dowling et al., 2022). Flexible climate action plans allow interventions to be adapted to local context. While analysis here shows how scaling obscures the characteristics of local areas emissions, the same process obscure social, economic, cultural and environmental features that, when embedded in the design of a policy or program, can help to make it more effective and equitable (Bulkeley & Betsill, 2005). Where regional and national climate action plans fail to be comprehensive and flexible – irrespective of whether that failure emerges from data scaling or by other means - analysis here suggests the impact can be meaningful for the efficacy of climate action and the impact across local areas will be skewed: A small number of local areas will see levels of climate action that are above the average of all local areas while a larger number will see levels of climate action that are significantly below average.

3.6 Conclusion

Several factors are understood to explain conflicting approaches to climate action – between levels of government or between actors more generally. Institutional arrangements, mobilisations of power, and ideology, for example, can all lead to conflicting climate action priorities. In the UK a significant literature critiques the Conservative government's climate record over the last decade through the lens of these factors (Averchenkova et al., 2021; Berglund & Bailey, 2023; Howarth et al., 2020). Underappreciated in existing literature, the way data is managed and analysed is shown here to be a further factor that can affect the way we understand the climate challenge.

Identifying that data scaling could affect climate action in the UK does not diminish the importance of a wider set of social, institutional and political factors for influencing the governance of climate action. Showing that the way data is managed and analysed can affect our understanding of the climate challenge, however, brings attention to methods of data analysis as an area in need of further attention. Scaling is one of a number of ways empirical methods can systematically influence our understanding of an issue and lead to unintended consequences (Simmons et al., 2011; Strube, 2006). This challenge will grow if more actors become involved in the governance of climate action and as the methods we apply to determine actions become more complex and opaque.

Further research is needed to explore the potential for data scaling to affect climate action. Applying time series data and exploring other geographic contexts can add to our understanding. In addition, research considering non-state actor's contributions to climate action and data scaling is needed. Varied levels of engagement in climate change from businesses (Revell & Blackburn, 2007), widely differing levels of commitment to action (Widerberg & Pattberg, 2015), and varied and sometimes conflicting approaches to action (Meath et al., 2016; Nunes et al., 2019) set the conditions for data scaling and other methodological choices to affect climate action and generate unintended consequences.

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4 Climate policy as social policy? A comprehensive assessment of the economic impact of climate action in the UK

Abstract

Co-benefits are central to the case for climate action but are side-lined in many economic analyses. This paper presents an evaluation of three dimensions of the costs and benefits of climate change interventions in six urban regions of the UK. Findings indicate that meeting the UK's 2033-2037 climate targets could yield £164 billion in total benefits. Notably, only 13% of these benefits are financial, in contrast to the 79% of which are social benefits. These social benefits include improvements in public health, reduced traffic congestion, and increased thermal comfort in homes. These results underscore the need for economic evaluations to expand their scope and move beyond the narrow financial cost-benefit analysis that predominates. Moreover, the magnitude of the social benefits underscores the need for integrating social and climate challenges in policymaking. Concurrently, the results demonstrate the sensitivity of the social benefits of climate actions to the normative aspects of empirical analysis. Determining whether emissions reductions in the transport sector, for example, should be achieved through the deployment of electric cars, expansion of public transport, and/or increases in walking and cycling requires both technical analysis and value-based decision making. Ensuring that decision-making processes are deliberate and transparent in empirical analysis is therefore critical. We conclude by suggesting that institutions such as the UK Climate Change Committee and Scottish Climate Intelligence Service should take the opportunity to be more explicit in the normative decisions embedded in their empirical work to demonstrate best practice for the wider research community.

Sudmant, Andrew; Boyle, Dom; Higgins-Lavery, Ruaidhri; Gouldson, Andy; Boyle, Andy; Fulkner, James; Brogan, Jamie

4.1 Introduction

The multiple crises currently facing the world create a uniquely challenging moment for climate policymaking. Coal powerplants that were due for retirement, for example, are being maintained to improve energy security, and responses to COVID-19 have led to reduced climate action in some parts of the world (Romanello et al., 2022).

At the same time, opportunities to intervene across multiple challenges are being revealed. Ukrainian self-determination, European energy security and global action on climate change, for example, are jointly supported by actions to reduce energy demand across the EU (Creutzig, 2022). Understanding the wider impacts of climate policies may therefore be uniquely important during this period of overlaps and intersecting crises known as the polycrisis (Lawrence et al., 2024).

So-called 'co-benefits' have remained largely absent from economic analyses of climate change despite compelling arguments being made as early as the IPCC's second assessment in 1996 that these wider impacts of climate mitigation are critical to the case for action. A number of reasons account for the limited role of co-benefits in the economic modelling of climate action. A lack of data and the uncertain, context-specific and contingent nature of many co-benefits has led to challenges drawing conclusions across literature (Gouldson et al., 2018). Controversy has surrounded the appropriate means of integrating the impacts of climate measures that affect people (health, wellbeing, heritage, culture), affect nature (biodiversity, ecological integrity), and are financial (Köberle et al., 2021). Imperfect means of measuring and operationalising co-benefits that are qualitative in nature and a high degree of variability of co-benefits between contexts underpin these challenges. This has led to significant difficulties replicating from studies and generalising findings in ways that have policy relevance (Sudmant et al 2024).

Several authors have argued that the case for a more comprehensive assessment of the costs and benefits of climate action is of limited value (Köberle et al., 2021; Weitzman, 2009). Knowledge of tipping points and severe consequences from insufficient action are argued to underpin the case for action, implying that a more nuanced analysis is a second-order consideration (Piontek et al., 2021; Weitzman, 2009). The increased uncertainty added by including a broader assessment of the net case for action, according to this perspective, can act to "obscure rather than clarify" policy options (Köberle et al., 2021, p. 1036).

Competing with these claims are literature highlighting the unique importance of co-benefits to a more robust response to climate change. Transformative opportunities have been found from combined approaches to climate change, energy, cost-of-living, and health crises (Romanello et al., 2022, 2023). Motivation to achieve co-benefits can overcome ideological barriers to supporting climate action, suggesting that co-benefits are key to the political case for climate action (Bain et al., 2016; Bergquist et al., 2020). The degree to which climate actions make the poorest in society better or worse off is significantly determined by the kinds of co-benefits and co-costs climate actions generate, making an assessment of co-benefits critical to a Just Transition (Colenbrander et al., 2017; Rauner et al., 2020; Robins et al., 2019; Svenningsen, 2019; Vandyck et al., 2020). Furthermore, unwarranted simplification and omission of complexities related to the quantification of climate action costs and benefits have been found as key driver of the macroeconomic losses found from climate action in some studies (Köberle et al., 2021).

In the UK, the wider costs and benefits of climate action have been a steadily emerging area of focus. The co-benefits of climate action in the UK that are highlighted by the Climate Change Committee (CCC) (a non-departmental public body tasked with advising the government on climate action) include improvements in health, air quality, energy access and security, job generation and economic development (CCC, 2019). Analysis from Forster et al (2013) of co-benefits considered by the CCC found that the net-benefits of climate action could be £85 billion and recent analysis by Milner et al (2023) found that the health benefits of climate actions in the CCC's pathways could exceed 2.5 million life years through 2050. Each of these papers is explored in more detail in the discussion section.

This paper adds to existing literature and discussion in three ways. First, analysis uses the most up-to-date UK government guidance for the measurement of the wider impacts of climate actions, including from the UK Green Book (HM Treasury, 2020), Transport Analysis Guidance (TAG 2021), and the UK Climate Change Committee (CCC, 2022). Utilizing these methods grounds our analysis in the existing approaches of UK government, which allows the results of this analysis to be relevant to ongoing policy development. In particular, comparison of the co-benefits from different interventions and in different urban areas in this analysis is relevant to the government's place-based approaches to climate action, which currently include Department for Energy Security and Net Zero's net zero hubs and Local Net Zero Accelerator pilots, and the development of local area energy plans (LAEPs) and Local Heat and Energy Efficiency Strategies (LHEES) in Scotland.

Second, this analysis includes three dimensions of climate impacts, allowing for a comparison of the relative case for action in a more comprehensive manner than has previously been published in the UK. The financial case for action in this analysis includes the direct costs and benefits, those relating to investment, operational costs and energy costs/savings. The social case for action is assessed by quantifying and monetizing a range of social benefits, including excess cold, indoor air quality, physical activity, traffic accidents, congestion, noise and the benefits of warmer homes ('home comfort'). The carbon case for action monetises the value of climate actions using the marginal abatement cost needed for the UK to meet its 2050 net-zero target. In this way the 'carbon case' for action captures the value of avoiding more costly future abatement.

Third, analysis explores how value-based decisions shape the co-benefits of climate interventions. Comparing results of this analysis with similar studies underscores how choices made during the modelling process—such as which interventions should be prioritised—reflect underlying normative frameworks. In the discussion and conclusion we discuss how surfacing and making explicit these normative aspects of empirical climate analysis may be increasingly important as climate action accelerates and as climate interventions expand into realms that are more socially and politically sensitive.

4.2 Methodology and Context

Modelling in this paper applies a version of the so-called 'mini Stern' methodology for climate action that has been applied in a number of local authorities in the UK (Gouldson et al., 2015a; A. H. Sudmant et al., 2017; Williamson et al., 2020) and in a number of international contexts (Colenbrander et al., 2016; Papargyropoulou et al., 2015; A. Sudmant et al., 2016). Named after the Stern Review (Stern, 2007), a landmark report on the economics of climate change in the UK, 'Mini Stern' analyses consider the economic case for climate action within a defined city or region using techno-economic models of low and zero carbon climate action interventions. In this analysis ~750 measures are applied in a scenario analysis designed to meet the equivalent of the UK's 6th Carbon Budget for each of 6 urban regions in our analysis. Using this approach, the costs and benefits of climate action are considered at the city region level. The full details of the methodology can be found in Appendix 1.

Analysis covers six urban regions which were selected to capture the diversity of urban contexts in the UK, including urban regions from each of the four nations (Scotland, Northern Ireland, Wales and England) and from cities with both relatively larger and smaller industrial sectors. The six urban regions are Glasgow, Belfast, Swansea Bay, Liverpool, Greater Manchester, and Cambridgeshire and Peterborough. London was not included in this analysis due to the transport model in our analysis not being capable of including some aspects of the London transport network. Analysis focused on the buildings and transport sectors where more than 80% of emissions from these cities are produced.

The UK's 6th Carbon Budget sets out the level of emissions the UK can emit between 2033 and 2037. Since the UK's emission are expected to fall in a consistent year-on-year fashion, the 6th Carbon Budget is often described as a reduction in GHG emissions of 78% in 2035 on 1990 levels. To align with the 6th Carbon Budget, scenarios in this analysis achieve 78% reductions in the GHG emissions that come from buildings and transport in each urban region (Figure 1).

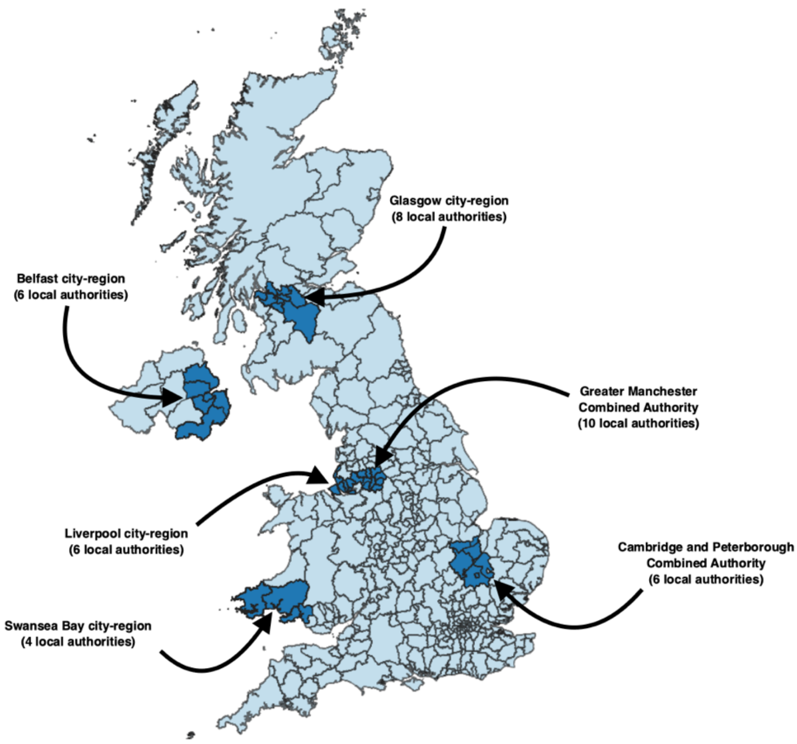

Figure 4-1: Urban regions included in the analysis

Local governments in the UK have responsibility over the provision of services and key powers over planning and development. The primary responsibility for climate action, however, is generally understood to lie with national government, which holds powers over taxation and environmental legislation and regulation, and which, unlike local government, is legally responsible for achieving the country's carbon budgets.

Applying best-practice UK government methods and datasets, including from the Transport Analysis Guidance (TAG) and the UK Green Book (a guide for the evaluation of government programs plans and policies), we conducted a cost-benefit analysis of interventions (individually and across scenarios of actions) to assess the financial case for actions. To assess the social case for action we monetized the impact of these actions for a range of social benefits, including excess cold, indoor air quality, physical activity, traffic accidents, congestion, noise and warmer homes ('home comfort'). To assess the carbon case for action we used the UK Government's Greenhouse Gas Emissions Value to estimate the carbon benefit of these interventions. The UK Government's Greenhouse Gas Emissions Value is a 'target-consistent' estimate of the carbon price consistent with the UK reaching its climate targets based on estimates of the marginal-abatement cost curve.

A high-level presentation of the approach of the analysis is found in Figure 2, using the transport sector as an example. The approach for avoiding double-counting of benefits follows guidance from the UK Green Book (HM Treasury, 2020) and guidance from academic literature including from . There are some limitations to this approach. For example, analysis did not consider how the health benefits from exercise change when air quality is improved. ThIn order to make the paper more succinct, detailed information on the sources of information that underpin the analysis, key assumptions and the flow-charts for the remaining sectors are found in Appendix 1.

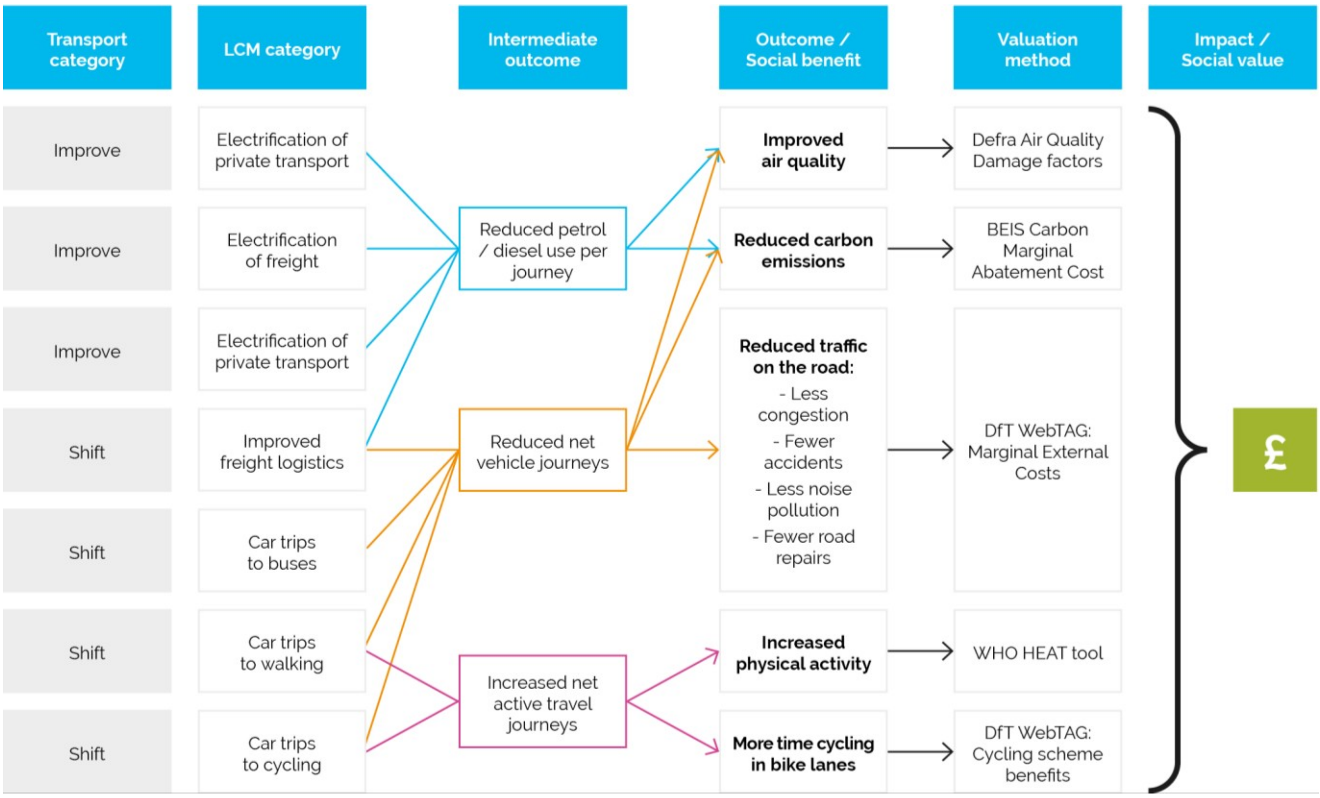

Figure 4-2: A high level representation of the methodological approach applied to calculate the value of co-benefits in the transport sector

Global benefits of climate action, including several that are foundational to the global case for action, are not assessed by this analysis. These benefits include the value of impacts avoided from reduced agriculture productivity (Ortiz-

Bobea et al., 2021), loss of biodiversity (Pires et al., 2018), heat stress (Santamouris, 2020; Vicedo-Cabrera et al., 2021), and desertification (Huang et al., 2020). In addition, several strategically important benefits of climate action are not assessed by this analysis. For example, the strengthening of zero carbon supply chains and increasing the UK's resilience to extreme climate events, which would both have widespread social and economic benefits, are beyond the scope of analysis in this study.

Table 4-1: Social costs and benefits of climate action included in analysis by type

Social Co-benefit	Definition
Congestion	The value of reduced time spent traveling and road repairs from reduced numbers of vehicles on roads
Infrastructure	The value of repairs avoided when infrastructure (in this case solely roads) are used less frequently
Air quality – transport	The value of public health benefits from reduced air pollution from transport.
Air quality – buildings	The value of public health benefits from reduced air pollution from buildings.
Physical activity	The value of health benefits from increased walking and cycling.
Excess cold	The value to the NHS of elimination visits to hospital attributable to insufficient heating.
Home comfort	The additional comfort to households when higher efficiency of appliances allows those appliances to be used more frequently.
Accidents avoided	The value of reduced vehicle repairs and lives lost from a change in the number of vehicle accidents.
Noise	The value to public health and worker productivity from reduced noise. This benefit is primarily from actions in the transport sector.

4.3 Results

In the following section we consider results across urban regions. Next, we compare findings between urban regions to understand how the scale and makeup of the case for climate action differs between the places. Finally, we explore how different measures lead to different costs and benefits of action.

4.2.1 The overall case for action

We found that a program of action consistent with meeting the UK's 6th carbon budget in the 6 urban regions of this analysis would generate £179 billion in total benefits and £164 billion in net benefits. 79% of all benefits are in the form of social benefits, while 8% come from the carbon benefits of action (the value of avoided future mitigation) and 13% from net financial savings (primarily in the form of energy savings). The financial case for action, including only the market costs and benefits of actions, is a significantly more modest: £8.7 billion with capital costs of £14.5 billion and savings from avoided operational costs and energy usage of £23.2 billion. The net financial case includes all the financial costs and benefits of climate actions. The total benefit case includes all of the costs and benefits of climate actions.

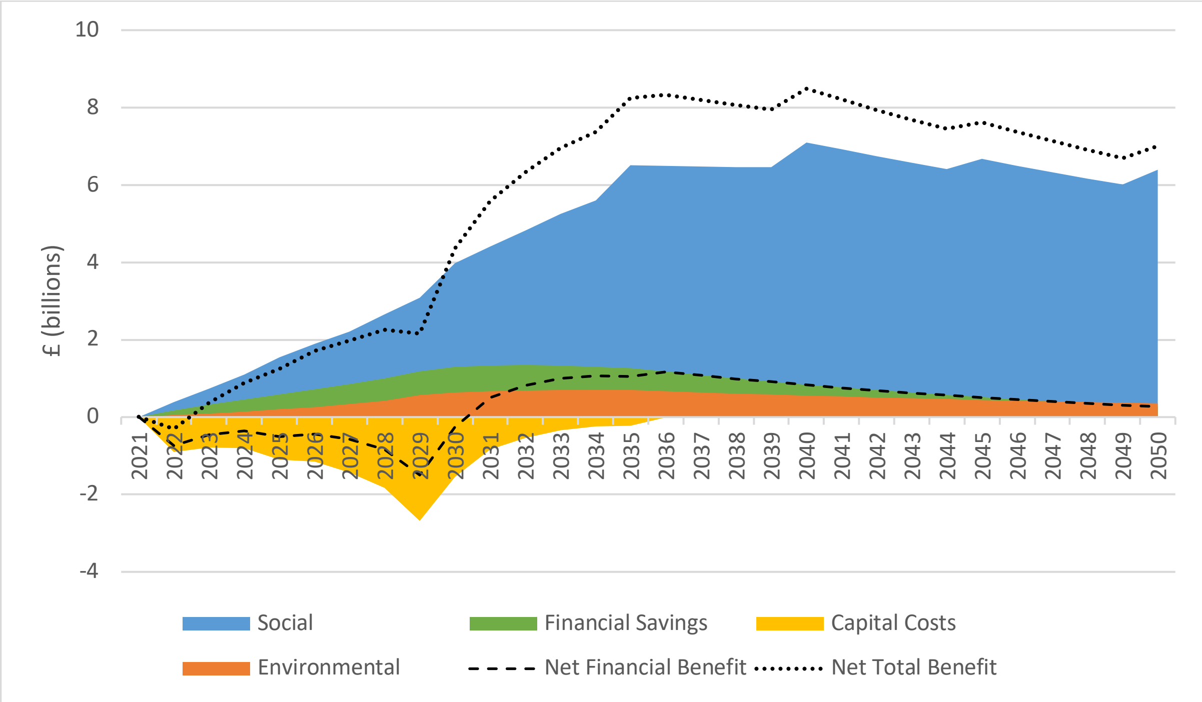

Figure 4-3: Discounted annual benefits of climate actions by benefit type, and capital costs

4.2.2 Climate action benefits by urban region and sub-benefit type

Figure 4 shows the non-market benefits of climate actions. The social benefits and carbon benefits are shown in Figure 4 by urban region on a per capita basis with differences between city regions reflecting different levels of opportunity for the implementation low and zero carbon measures. The social benefits of climate action are significantly greater than carbon benefits within and between cities – across cities the social benefits of climate action are £16,552 per capita, while the carbon benefits are £1,586. The scale of benefits also differs significantly between urban regions. Carbon benefits on a per capita basis are largest in Glasgow (£2,119 per capita) and smallest in Belfast (£1,233 per capita). Similarly, social benefits are largest in Glasgow (£23,039 per capita through 2050) and smallest in Belfast (£8,404 per capita through 2050). Congestion improvements are the largest source of benefits across urban regions, with physical activity being the next greatest category. Congestion improvements are generated by climate measures that shift travel from private vehicles to buses, walking or cycling. The benefits of congestion and physical activity are 86% of the total social benefits of climate action.

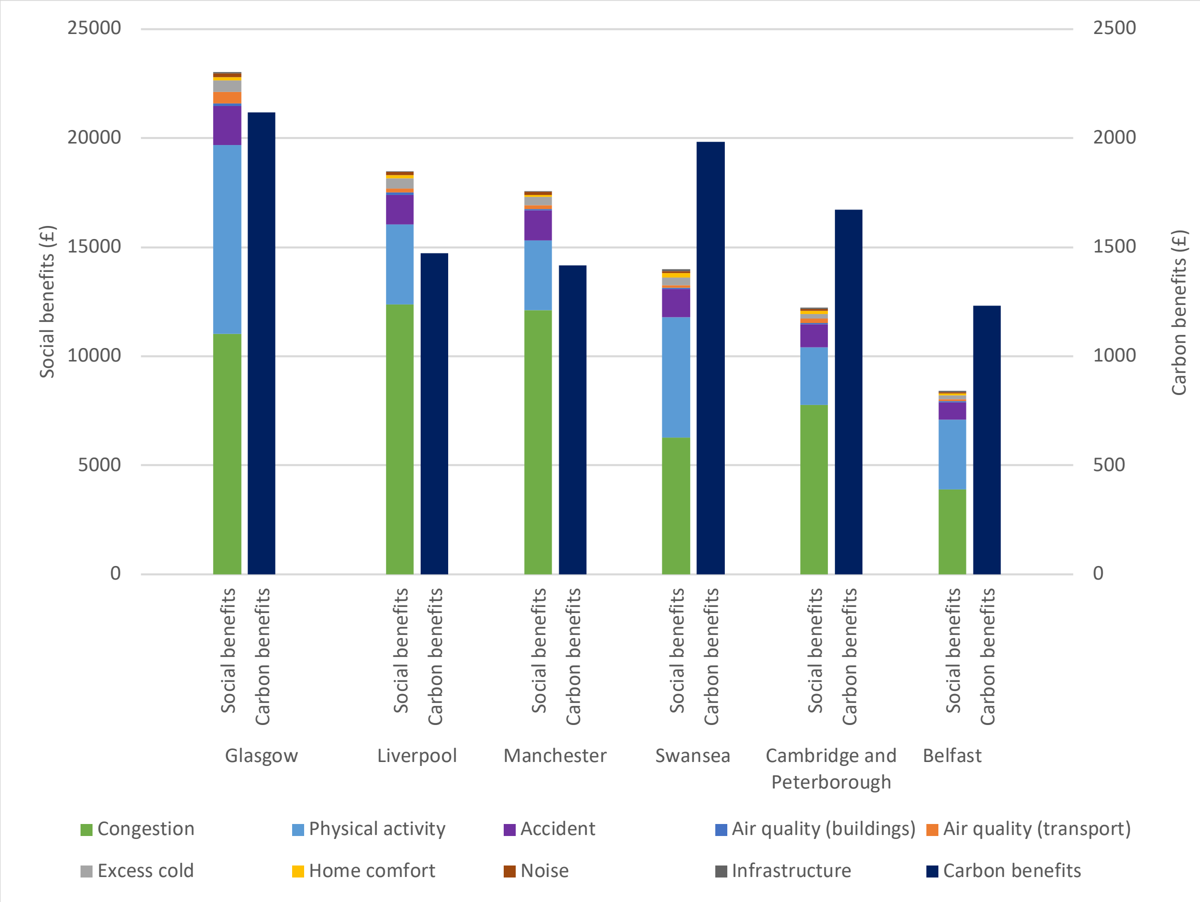

Figure 4-4: Per capita social benefits by urban region

Figure 5 investigates the market benefits of climate actions between urban regions via the net financial benefits of GHG mitigation on a per capita basis. Mean per capita net financial benefits across urban regions are £1,011 from 2022 – 2050, ranging from £326 in Glasgow to £1,645 in Belfast. Interventions in the transport sector are the most cost-effective in all urban regions, with the domestic and non-domestic sectors generating net financial returns in some urban regions and net costs in others. The financial savings are primarily in the form of energy expenditure savings.

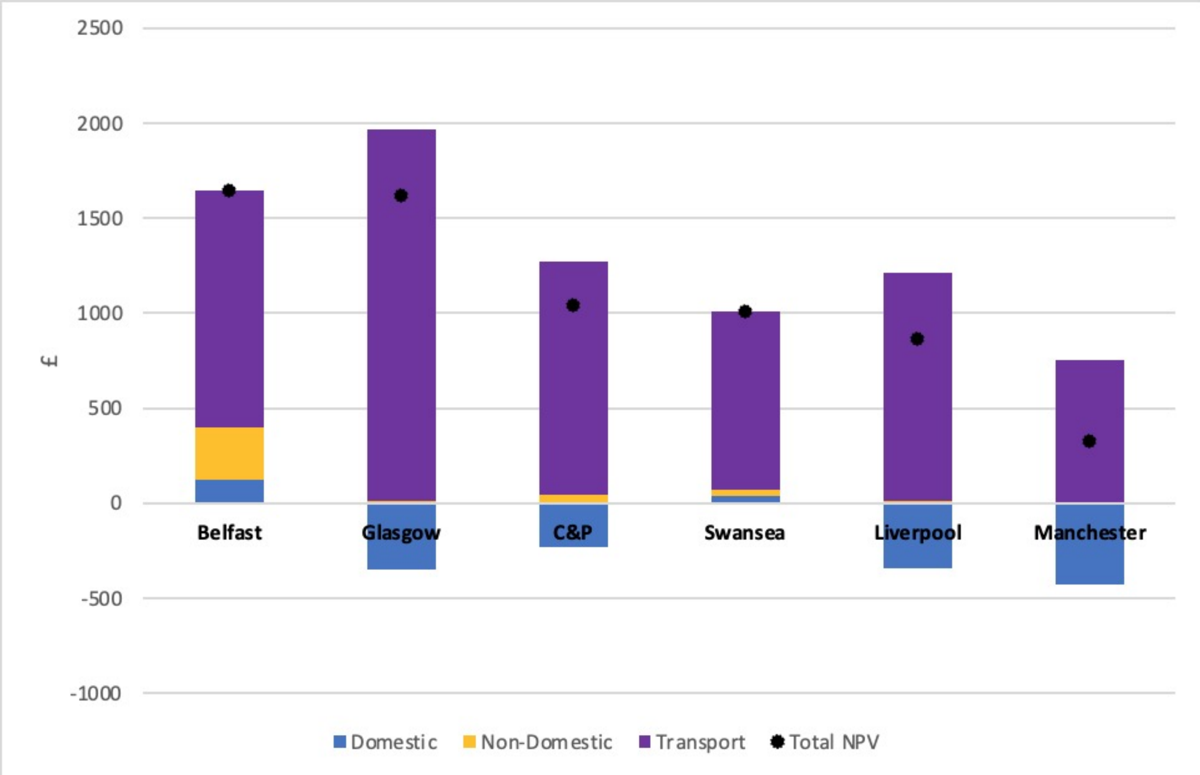

Figure 4-5: Per capita net-present value of financial case for action on a per capita basis

4.2.3 Climate action benefits by measure

Figures 6 and 7 show the cost per tonne of GHG savings if social, carbon or financial benefits alone were used to value mitigation measures. Both figures present the same data at different resolutions. Coloured regions indicate the locations of the largest number of individual measures of specific measure-type clusters. Measures are ranked by their average social benefit per tonne of GHG emissions saved, with measures shifting people out of private cars delivering social benefits that are too large to capture in Figure 6.

In the majority of cases (7/13) the financial benefits of actions – the net energy savings and operating cost savings from measures – are larger than the social and carbon benefits of measures. In four cases the social benefits of climate action are larger than the carbon and financial benefits of action and in only two cases the carbon benefits of action are larger than the social and financial benefits of action. These results show that while the largest aggregate benefits from climate action come from the social benefits of action, for a majority of interventions the financial case for action (primarily from energy savings) provides a more compelling case for action.

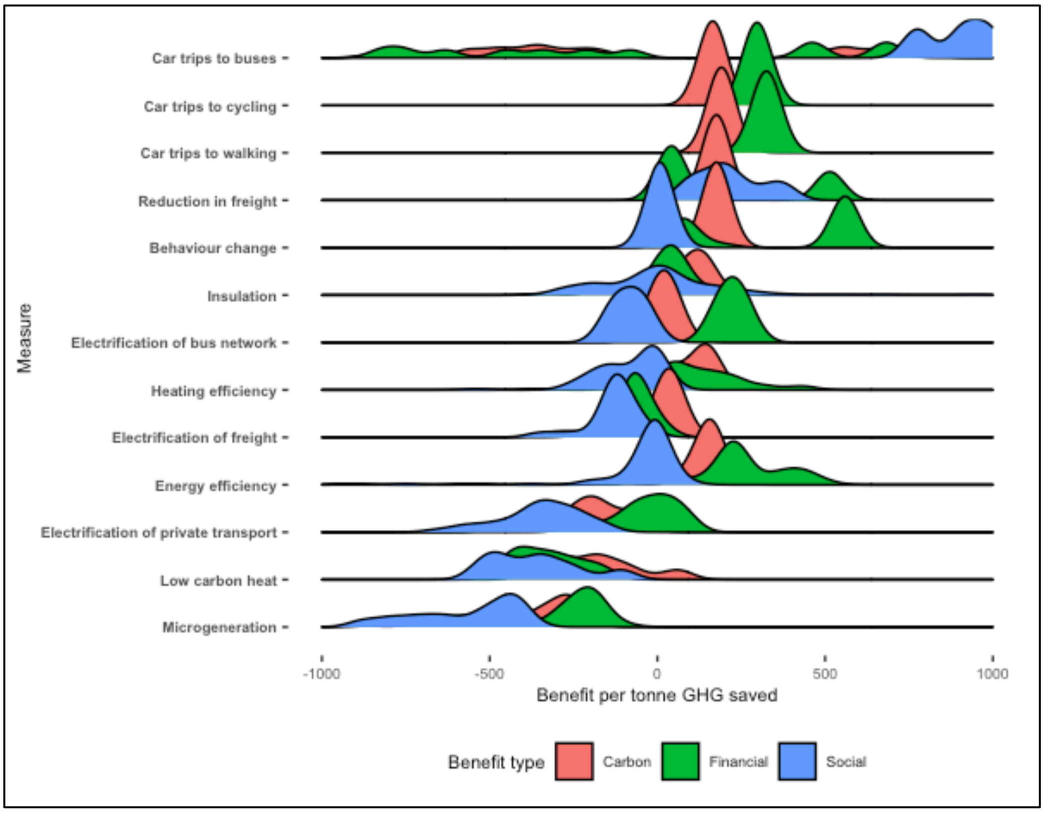

Figure 4-6: The density of social, financial and carbon benefits of climate action between -1000 and +1000 £ per tonne GHG savings. The same data is shown in Figure 6 at a different resolution.

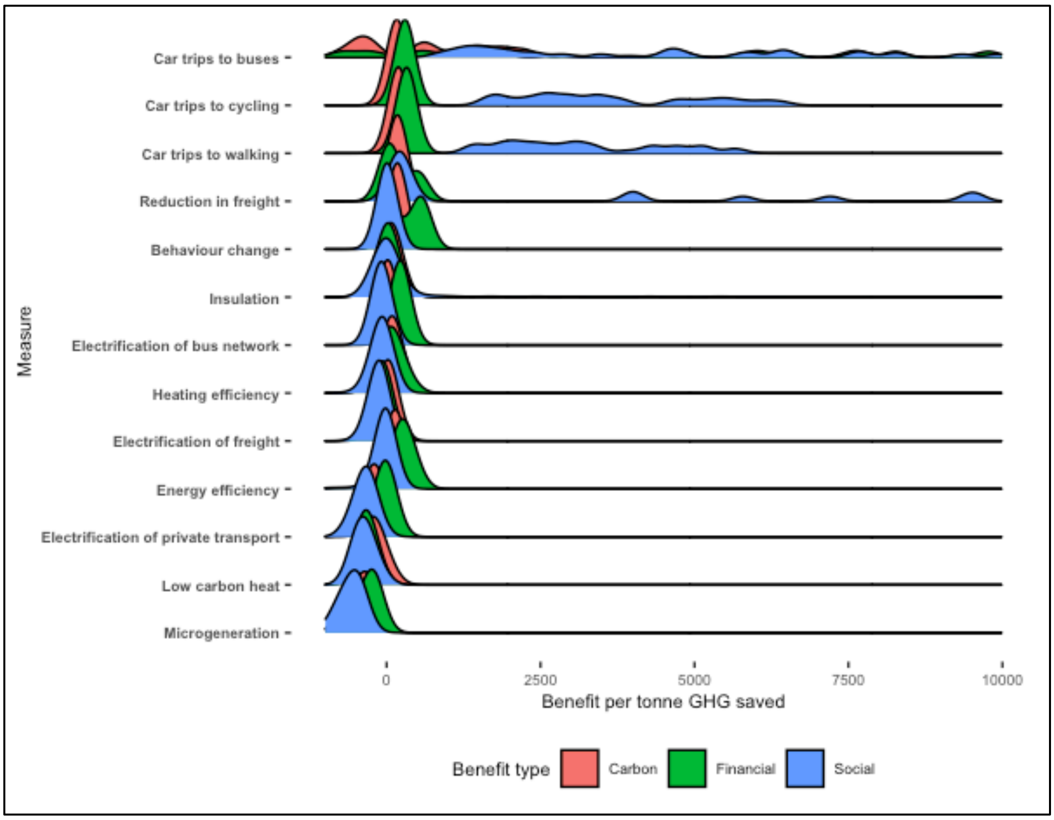

Figure 4-7: The density of social, financial and carbon benefits of climate action between -1000 and +10000 £ per tonne GHG savings. The same data is shown in Figure 5 at a different resolution.

Figures 6 and 7 show where the majority of individual measures cluster but do not take into account the scale of GHG savings from individual measures. In Figure 8 marginal abatement cost curves rank measures from most to least cost effective in order to explore the extent to which different kinds of benefits effect the scale of cost effective (net benefit generating) climate action.

A significant literature explores the limitations of marginal abatement cost curves, including around transaction and policy costs, the effect of interactions, and unintended consequences, see Vogt-Schilb & Hallegatte (2014) for further discussion. Acknowledging these limitations, marginal abatement cost curves (MACC) are used here to provide a high-level illustration of the relative scale of interventions and their costs, in line with wider literature that used MACC curves for the same illustrative purposes (Ibrahim & Kennedy, 2016; A. H. Sudmant et al., 2017).

Figures 6 and 7 demonstrate that the concentration of social benefits in a small number of measures leads to a smaller volume of emissions that can be mitigated at a negative cost if assessment only considers the social benefits of climate action (as well as the direct costs of interventions). The total volume of emissions that can be mitigated at a negative cost is 74.3Mt CO2e when only social benefits are considered, but 107Mt CO2e (44% more) when financial benefits are considered and 128Mt (73% more) when carbon benefits are considered. Figure 7 thus shows that the carbon benefit of climate actions, despite contributing a relatively small share of total climate benefits (Figure 2) and being less important than financial or social value for specific interventions (Figures 5 and 6), plays an important role in supporting the business case across a large set of interventions. Consequently, the carbon benefit of climate action leads to the largest volume of negative cost GHG savings.

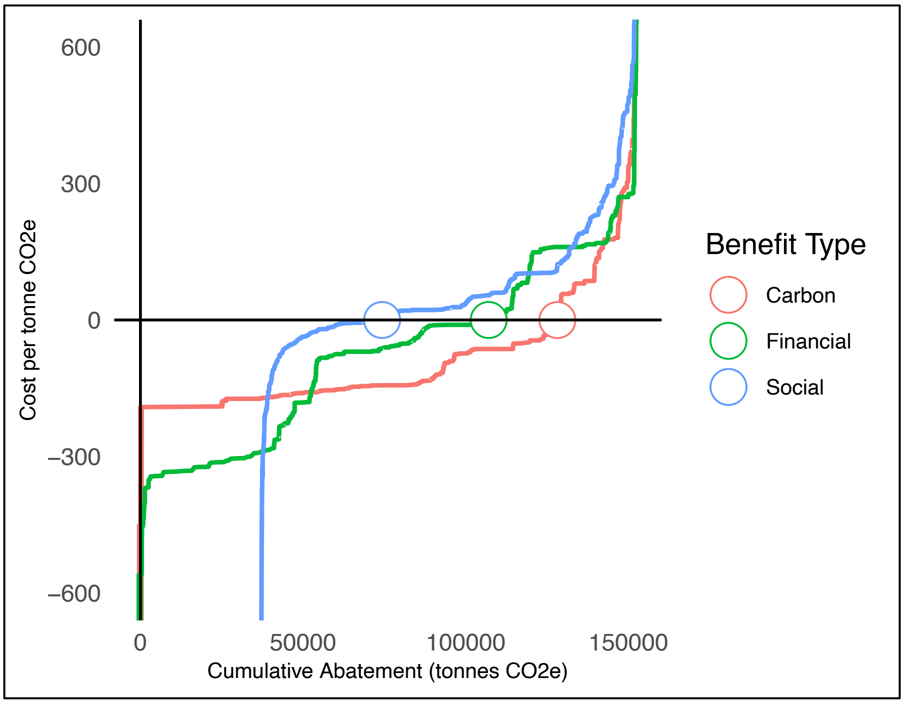

Figure 4-8: Marginal abatement cost curves developed from the social, carbon and financial costs of climate action.

To explore the way that different dimensions affect the case of climate actions, Figure 9 shows low and zero carbon measures coloured by measure type on a ternary plot. A ternary plot shows the relative share of the total value of each measure contributed by each of the three dimensions. Three findings are notable. First, while social benefits are very large for measures that shift travel from private cars to non-motorised and public transport options, the financial benefits are also very large (Figure 6), suggesting that developing a case for implementing these measures may not strictly depend on the development of the social case for action. Second, specific types of measures are shown to depend on a carbon or financial case for action. Electrification of freight and transport depend on the financial case for action while heating and energy efficiency measures depend on the carbon case for action. Finally, few measures are found near the centre of the diagram, suggesting that it is combinations of two of the financial, social and carbon cases for action that are important to the case for action for most measures.

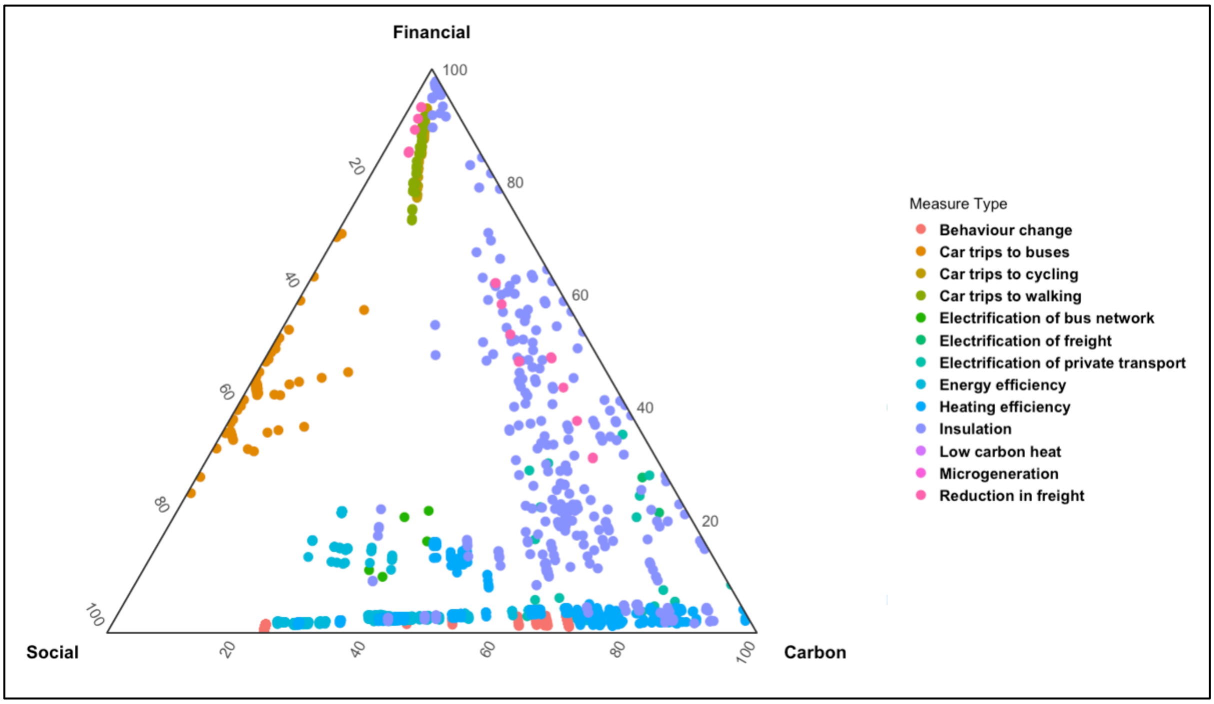

Figure 4-9: The relative social, financial and carbon case for measures by type. Each axis captures the share of total benefits from a benefit type

4.4 Comparing the Financial, Social, and Carbon Cases for Climate Action

4.2.3.1 The Financial Case for Climate Action

The financial benefits of implementing low-carbon measures are found to more than offset the capital and operating costs of action. Across all sectors and urban regions – representing 13% of the UK's population – the net cost of achieving mitigation commensurate with meeting the sixth carbon budget, is -£8.7 billion with capital costs of £14.5 billion and savings from avoided operational costs of £23.2 billion. Financial savings are found to constitute 13% of the total benefits of climate actions and are the largest source of benefit for seven of the thirteen types of measures assessed.

These figures align with literature assessing urban climate action in the UK and other wealthy nations. Williamson et al. (2020) and Gouldson et al. (2020), for example, both found that GHG emissions could be reduced more than 40% in ways that generate financial returns in cities in the UK. Analyses for New York (New York State Climate Action Council 2022), San Antonio (City of San Antonio Office of Sustainability 2021) and Toronto (Ibrahim and Kennedy 2016) similarly found significant potential for cost-negative climate action. These findings present a more optimistic impression of the cost of climate action, however, than current government assessments.

While the CCC has been cautious about placing a definitive figure on the net cost of action, the 6th carbon budget concludes GDP could be increased by 2% by 2035 with an annual cost of 0.6% of GDP in the early 2030s falling to .5% of GDP by 2050. These figures for the net cost of action are smaller than previous CCC analysis that expected costs to rise to 2% of GDP by 2050. The increase in GDP, and reduction in net annual costs, are primarily the result of reduced expenditure on energy (CCC, 2020). Research from the Office of Budgetary Responsibility (OBR, 2021) found the total costs of mitigation in the UK to be £1.4 trillion, with £1.1 trillion being offset through financial savings.

The differences between the estimates from the CCC and OBR and the results of this analysis can be significantly attributed to differences in the scope of analysis. Where analysis here is limited to the buildings and transport sectors, the CCC and OBR analysis cover all sectors of the economy, including abatement challenges in sectors such as land-use and industry. In addition, analysis here achieves the 6th carbon budget, but not the further reductions necessary to meet net-zero. These 'final' emissions are generally understood to be the most costly to abate, although CCC has noted that literature frequently has been too conservative, with innovation and market forces resulting in lower costs than previously projected (CCC, 2022).

4.2.3.2 The Social Case for Climate Action

The social benefits of achieving the 6th carbon budget in the city regions in this analysis is £142 billion and 79% of the total benefits of climate action assessed by this analysis. These figures are significantly larger than estimates in existing literature. Similarities in effect sizes at the level of individual interventions suggest the difference between this study and other literature are largely attributable to the scale at which climate measures were implemented. In the following we specify the methodological differences between this study and similar literature. In the conclusion of this section and continued in Section 5.2 we consider what it means for empirical analysis of co-benefits that methodological choices can underpin significant differences in our understanding of the case for climate action.

Previous work completed for the UK Climate Change Committee by Ricardo Economics (Forster et al., 2013), modelled the medium abatement potential of the fourth carbon budget. Across complimentary sectors in analysis here and in Forster et al. (2013), the largest benefits originated from reductions in congestion and the second-largest benefits from increased physical activity. The scale of benefits, however, is significantly different between studies. While Forster et al (2013) found annual benefits across transport and building sectors worth approximately £80 per capita, this analysis found benefits of £552 per capita.

A similar divergence is found between our results and those in Milner (2023). Milner et al (2023) model mortality improvements across England and Wales (2021 – 2050) measured in cumulative life-years gained from the CCC's Balanced Pathway and Widespread Engagement pathway. Assessing air quality improvements from the transport sector, this analysis estimated mean annual per capita benefits of £7.43 from PM2.5 and PM10 reductions. This value is significantly larger than the £60,000 per life-year gained in Milner et al. (2023), which equates to £1.83 per capita. Total co-benefits arising from increased physical activity scaled to the level of the UK (to enable comparison) are £225 billion from this study and £17 billion in Milner et al (2023), if £60,000 per life-year gained is applied.

Per capita health benefits are therefore approximately 4-13x larger in this study than in existing research. Differences in effect sizes from interventions, however, are dramatically smaller. Analysis here, for example, found health benefits of approximately 14 pence per km, just less than double the £0.08 per km implied (at £60,000 per life-year gained) by Milner et al. (2023), and considerably less than the £0.80 - £1.10 per kilometre cycled in direct health benefits found in other literature (eg Davis, 2014). Similarly, congestion benefits in this analysis are approximately 7 pence per vehicle-kilometre avoided, smaller than comparable literature (Arregui & Parry, 2020) and to the 12.4 pence per vehicle-kilometre (in 2012 prices) in Forster et al. (2013).

Differences in the scale of social benefits from climate action between this study and wider literature are therefore primarily driven by dramatic differences in the scale of deployment of certain interventions rather than valuation methodologies. Daily mean active travel increases by 2.84 km per person by 2037 in this analysis, but only 0.34 km pp by 2050 in Milner et al (2023). Forster et al. (2013) models a reduction in vkms of 1.7% through 2050 while analysis here models a reduction of 13% of vkms.

Whether the scale of non-motorised measures employed in this analysis is realistic is in part a technical question to be assessed based on parameters found in literature and the characteristics of the area being assessed. In this context we note that co-benefits in this analysis are capped according to HEAT methodology, fall below HEAT thresholds and are aligned with recommendations from other literature (eg Brand et al., 2021; Jarrett et al., 2012). Even at the level of implementation in this analysis, cycling kilometres per capita would be significantly below the levels in Denmark and the Netherlands today (Mueller et al., 2018), and comparable to the rates achieved in Paris over the last 2 years (Meeks, 2023). Whether achieving GHG reductions targets without rapid and large-scale reductions in car use beyond what is suggested in this analysis has also been questioned, including from literature focusing on the UK context (L. Winkler et al., 2023)

Insofar as assessing the realism of scenarios is a technical question, however, it is also a question that is deeply and fundamentally normative. Whether a future transport system should focus on non-motorised mobility, enabled by 15-minute cities, mixed development and high-quality public transport, or have a relatively larger focus on zero carbon private transport options, is in part determined by the perspectives of the team engaging in the modelling exercise. The same attitudes, perceptions, political views, habits and aspects of the social environment that determine whether an individual is willing to cycle (D. P. Willis et al., 2015), are undoubtedly involved when a modelling team considers whether individuals are willing to cycle. The scale and nature of co-benefits from climate action are therefore significantly determined by value-based decisions that are frequently embedded deep in the appendices of empirical modelling exercises. In Section 5.2 and the Conclusion we consider what this means for empirical work on the co-benefits of climate action and the modelling of pathways to net zero.

4.2.3.3 The Carbon Case for Climate Action

The discounted total value of carbon saved from mitigation in this analysis is £13.6 billion across urban regions. This amount represents 8% of the total value of the benefits of climate actions.

Carbon values are used by the UK government for valuing changes in GHG emissions resulting from policy interventions. Carbon values represent a monetary value placed on one tonne of carbon dioxide equivalent, and differs from the ‘price of carbon’, which represents the observed price of carbon offsets in a market (for example the UK or EU Emissions Trading Schemes). These values also differ from the social cost of carbon, a measure of the long-term damage caused by GHG emissions. Since 2009, the UK has applied a ‘target consistent’ approach to estimate the value of each tonne of carbon whereby the carbon value is calculated as the marginal abatement cost of meeting GHG targets. The carbon cost is therefore a measure that is specific to the UK’s national context, both in terms of its GHG emissions and opportunities for mitigation.

Since the value of abatement will be the same irrespective of the source of savings (i.e. the sector or measure), the benefit of using carbon values concerns how the carbon value changes the cost/benefit analysis of a program or policy. Results here show that despite being a relatively smaller component of the cost/benefit calculation across all interventions and urban regions, the carbon value plays a critical role in the domestic and commercial sectors. Indeed, of the three dimensions of benefits from climate actions, the carbon value of action achieved the largest negative cost volume of emissions savings from actions (Figure 7).

4.3 Towards a more Comprehensive Approach to Climate Action

4.3.1 The Importance of Non-Financial Benefits for Advancing Climate Action

Of the total benefit of climate action in the urban regions in this analysis, 13% comes from financial savings, a share that is likely overstated due to various critical global benefits of climate action, including to agriculture productivity (Ortiz-Bobea et al., 2021) and biodiversity (Pires et al., 2018), not being considered. The financial case for climate action, however, has been gaining substantial political and academic traction.

Even before the recent rise in energy prices, a growing body of literature presented the transition to a net-zero society as a financial opportunity. Climate policies can correct market failures such as those associated with fossil fuel subsidies (Monasterolo & Raberto, 2019), and support innovation, productivity, and long-term economic growth

(Stern, 2022). Recent energy-economy analyses have found financial savings in the trillions of USD from a shift to green technologies (Jaxa-Rozen & Trutnevyte, 2021; Shiraki & Sugiyama, 2020; Victoria et al., 2021; Way et al., 2022).

These developments, and growing urgency to avoid tipping points in the earth's climate raise a reasonable question about the value of wider assessments of the case for climate action. Analysis here supports other literature in this field by suggesting that a better understanding of climate action's non-market benefits may have two key roles.

Firstly, even as the aggregate financial case for climate action is compelling, the wider benefits of action are important to the case for specific, and in some cases critical, interventions (Ürge-Vorsatz et al., 2014; Grubb et al 2022). Financial and non-financial costs of action are frequently concentrated for particular subsets of the population, in particular geographies, for particular levels or departments of government, or for particular kinds of actors; for example, owners of homes but not renters (Green and Gambhir, 2019). These costs emerge from the need to reskill millions of workers (Bowen and Kuralbayeva, 2018; Robins et al., 2019), the burden on the financial system from stranded assets (Mercure et al., 2018), the need for mobilising and redirecting billions of investment capital (Giglio et al., 2021) and from the challenge of unlocking social and economic systems tied to fossil fuels (Ivanova et al., 2018). Many of these costs are financial, but the costs of an unjust transition are also to public health and to the social and cultural fabric of communities (Beatty & Fothergill, 1996). In analysis here, measures to implement heat pumps in domestic homes are in many cases only cost-effective when social or carbon benefits are considered. Similarly, measures to improve insulation in commercial buildings and to expand public transport systems generate negative or negligible returns in the absence of consideration for carbon and social benefits.

Secondly, the wider benefits of climate actions may play an important role making the social and political case for action (Bain et al., 2016; Bergquist et al., 2020). Literature has found that 20-40% of urban GHG emissions are mitigable in ways that generate financial returns, but deeper and faster reductions that align with global carbon budgets are found to require significant loss-making financial investment (Colenbrander et al., 2016, 2017; Gouldson et al., 2015b; A. Sudmant et al., 2016; Williamson et al., 2020). This research suggests that while a transition of the energy-system as a whole may generate net financial returns (Jaxa-Rozen & Trutnevyte, 2021; Shiraki & Sugiyama, 2020; Victoria et al., 2021; Way et al., 2022), urban areas may concentrate legacy capital investments that are costly to replace or retrofit for a zero carbon future, emphasising the importance of understanding the non-market benefits of action. Financial benefits are the largest source of benefit for seven of the thirteen types of measures assessed in this analysis. However, the social benefits of climate action generate the largest aggregate benefits and the carbon benefits of action generate the largest volume of GHG emissions reductions that have a negative cost, generating a more comprehensive case for action.

4.3.2 The Place-Specificity of Co-benefits and the need for Surfacing the Normative Aspects of Co-benefit Analysis

An understanding of the wider costs and benefits of climate action provides a means of engaging with the full scope of the impact on people's lives from the transition to a net-zero society. Climate actions both complement and conflict with wider social, economic and environmental priorities with the extent of those complements and conflicts found to vary significantly between places in this analysis.

The GHG savings from electrifying the bus network ranges from as little as 4 kt CO_2e in Swansea, to more than 500 kt CO_2e in Liverpool. Electrification of the freight network generates financial benefits of £10/tonne GHG mitigated in Manchester, but costs £79/tonne in Cambridgeshire and Peterborough. The social benefits of insulation vary from £223/tonne GHG saved in Cambridgeshire and Peterborough to £285/tonne GHG saved in Belfast.

The differences in the costs and benefits of action between regions are driven in part by the technical and built environment context. The scope for increasing non-motorised and public transport is relatively higher in Glasgow than Cambridgeshire and Peterborough due to Glasgow's relatively higher level of density, which allows more trips to be possible by foot, bicycle or bus.

The social benefits of climate actions, but not the carbon benefits or financial benefits, are also affected by the socio-economic context. An increase in walking and cycling that reduces private car travel reduces the same amount of GHG emissions and energy expenditure in Glasgow as in Cambridgeshire and Peterborough. The benefits to public health from this shift, however, will be larger in Glasgow due to the population being relatively older and facing higher rates of a range of public health ailments.

More research is urgently needed to further explore how aspects of local context affect the benefits and costs of climate actions and the distribution of those benefits and costs. Even as the overall benefits of action far out-weigh the costs, the scale of benefits from non-motorised transport options, for example, may accrue disproportionately to those members of the population who can more easily increase walking and cycling – a younger and more urban population (Davis, 2014). Similarly, the costs of retrofitting older buildings may fall disproportionally on an older and more rural population (Kerr et al., 2018).

Contrasting with the findings that are unique to urban regions, a set of common findings also exist across urban regions. Measures that shift travel from private cars to non-motorised and public transport options are found to generate substantial social and financial benefits in all places. The case for heating and energy efficiency measures is found to be driven by carbon savings rather than social or financial benefits in all urban areas. The dimension of cost/benefit (social, carbon and financial) found to be largest for an intervention in one urban region is almost always found to be the largest dimension of cost/benefit for that intervention in all regions. Across all types of measures in this analysis at most two of the three dimensions of costs and benefits (financial, social and carbon) is found to underpin the case for action.

Common aspects of the socio-economic and technical context underlie these findings. Differences between the results in this study and literature assessing similar measures in the same or similar contexts, however, highlight the importance of methodological choices for shaping our understanding of the co-benefits of climate action. Per capita differences in the health benefits of climate action, for example, are found to be 4-13x larger in this analysis than in existing literature applying UK CCC climate action pathways (Forster et al. 2013; Milner et al 2023), due to larger increases in active travel in this analysis.

Surfacing the methodological decisions that lead to different conclusions about the scale of some co-benefits may be increasingly important. While climate action to date in the UK, US, EU, and China has been led by action in the electricity sector (Boehm et al 2023), climate action in the future in these and other nations will need to shift to emissions from buildings, transport. Action will therefore necessarily shift from urban hinterlands to urban centres, from a relatively small number of actors to every household and business, and from a set of interventions that are often highly technical to interventions such as bicycle riding and thermal insulation that are prosaic but politically and socially complex. Climate action will also need to take place orders of magnitude more quickly.

Approaches for making complex methodologies more transparent and nuanced analyses more accessible include documenting research decisions, making datasets, code, and methodologies more easily accessible, and greater emphasis on comparing results with existing literature (Gelman, 2018; Yarkoni, 2022; Sudmant; Creutzig and Mi, 2024). Researchers can also differentiate between the concepts of generalisability and replicability to support the development of a more integrated and interdisciplinary research (Sudmant; Creutzig and Mi, 2024).

Generalisability refers to the extent research findings in one context may apply in another context. The scale of social benefits from shifting to non-motorised transport, for example, are likely to generalise across the urban UK and to other wealthy urban contexts where levels of physical activity are significantly below recommended levels, where air quality and risks of traffic accidents are comparable, and where the demographic profile is similar. In developing contexts, however, where there are frequently many more young people than old, and where health risks from traffic accidents and air quality faced by those using non-motorised transport are much higher in some cases (Borck & Schrauth, 2021; Damani & Vedagiri, 2021), further research is needed.

Narrowly, the concept of replication refers to the challenges associated with confirming the results of studies. More broadly, the concept of replication engages with the extent an analysis appropriately captures a concept through the construct validity of the frameworks and operationalisations that are applied. Health co-benefits from physical activity in this analysis, for example, are operationalised with relationships between cycling/walking, age-specific mortality, and the value of a life year from the UK Greenbook. This approach is different from an approach that applies a quality-adjusted life year, or a disability adjusted life year. More generally, interrogating both the approach to operationalising each co-benefit in this analysis and the choice of co-benefits fall within a discussion around the replicability of this research.

Many ways that researchers and policymakers interact with co-benefits analysis will not need to strictly differentiate between discussions that relate to replication and to generalisability. As the two concepts intertwine, however, clearly specifying these concepts can help to prevent miscommunication. Confusion between replicability and generalisability, for example, can underpin confusion between the need to understand the health benefits of climate action in the urban UK and other wealthy urban contexts, and the health benefits of climate action as they apply to the urban Global South or to urban contexts in general. Applying these concepts can also help to provide a bridge between different sources of knowledge. Focusing on the replicability of the health co-benefits of climate change

4.4 Conclusion

Including the social impacts of climate actions in economic assessment of climate action enhances the case for action. Arguably of greater importance, integrating social and climate analysis is a first step towards integrating policy approaches and action.

Employing replication and generalisability as boundary objects, concepts that are commonly understood across disciplines (Akkerman & Bakker, 2011; Star & Griesemer, 1989), offers a means to develop more integrated and interdisciplinary approaches of climate assessment.
The concept of replication serves as a meeting point for research that considers the different kinds of impacts that can be considered co-benefits and the different ways those co-benefits can be operationalised through methodologies. The concept of generalisability serves as a meeting point for research considering when co-benefits research in one context can provide insight into the wider impacts of climate action in other contexts.

The development of more integrated approaches to the economic assessment of climate actions can also benefit from more deliberate and transparent approaches to the normative aspects of co-benefits analysis. Leadership in making normative assumptions more visible could come from climate institutions in the UK, including the UK Climate Change Committee, The Yorkshire and Humber Climate Commission and The Scottish Climate Intelligence Service. More explicitly, presentation of how the value-based decisions the empirical work from these and other key actors can guide best practice for the wider research community. It can also advance our understanding of how the empirical analyses we are developing capture or conflict with different visions of a net zero future.

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5 Conclusions and Reflections on this Thesis

With my background in the natural and economic sciences I began this PhD with the intention of making a contribution to empirical urban environmental literature. In particularly, I wanted to advance the use of novel empirical methods and approaches for informing practical urban climate action. Writing today, the full extent of my PhD's evolution is apparent. Less a contribution driven by the data and methods themselves, the chapters of this thesis offer a window into the evolution of my understanding of urban environmental challenges, and I hope, some insight into how empirical urban environment research and discourse can be developed more coherently.

In this conclusion I seek to achieve two things. First, I reflect on my (rather lengthy) journey to submitting my PhD thesis. Second, I reflect on what the chapters of this thesis can contribute to the development of a more interdisciplinary quantitative urban environmental literature. To achieve this second aim I start by considering the limitations of my research design and methodology. With these limitations in mind I then discuss the findings that are specific to each chapter (5.2) and that cut across these chapters (5.3). Finally, I consider how these findings and the associated claims I make complement and conflict with existing literature (5.4) and suggest a roadmap for future research (5.5).

5.1 Personal Reflections

Handing in this thesis is the conclusion (I hope) of an eight year journey. In truth, however, the journey has been dramatically longer. I spent five years as a researcher at Leeds working to understand how the tools and practices of economic analysis can contribute to our understanding of urban climate action before starting my PhD. A year during my Masters was spent learning how my undergraduate degree in economics did, and conclusively did not, help to understand how environment policy is made. My undergraduate degree was spent prevaricating between my interest and passion for biology and environmental science and a nagging feeling that 'answers' to environmental challenges came from economics and policy rather than science.

The specifics of my path are unique, but thematically this journey marks me as something of a charature of a social sciences PhD candidate. From biology to economics, economics to environmental policy, and environmental policy to whatever, you reader, judge to be my field of work now, each step I have found myself attempting to build a wider perspective on environmental challenges. Below are the set of personal findings from my journey. If each of these is a timeworn trope, if not a cliché, it is because my own journey has been an archetype of an empiricists discovery of social science.

5.1.1 Being uncomfortable is the whole point

If I'm asked whether someone should do a PhD, and the asker is asking genuinely and not as a way of poking fun at me for spending at least 8 years on my own PhD (which is usually the case), I would try and explain to them the unique discomfort of doing a PhD[3]. I am not sure, strictly speaking, that I know more than I did when I started my PhD 8 years ago. Knowledge and ideas I have gained have to be set against knowledge and ideas that quietly atrophied. Saying that I know more is too bold.

But I know much more today about what I don't know. This journey has cultivated a sort of comfort in intellectual discomfort. I've come to recognize that the topics I care about and hope to dedicate my work towards require a scope of knowledge and experience far beyond what one person (or at least this person) could carry. This realization has been both humbling and motivating, pushing me to continually seek new perspectives and challenge my own assumptions.

[3] Spending 8 and arguably 18 years on a PhD effectively prevents me knowing if the PhD experience is indeed *uniquely* discomforting. Resting on my economics background I am going to take it as an assumption the PhD is in fact uniquely unconfortable.

A key to nurturing this mindset has been developing a practice of reflexive criticality. This approach involves constantly questioning not just the subject of my research, but also my own position within it, the methodologies I employ, and the broader implications of my work. It's a process that can be uncomfortable and often leads to more questions than answers, but it's also something that has made my PhD journey rewarding.

5.1.2 Research is normative all the way down

This observation, above all others, reveals how wide-eyed I remain outside of the nicely formatted spreadsheets of empirical research. Embedding a need to reflect on the role of values has more than any other reflection affected how I think I have changed as a researcher. Values are everywhere. In the way we as researchers choose the topics and 'challenges' to apply our time to, in the questions we develop to consider those challenges, in the methodologies we think are most appropriate and the archetypical examples of the use of those methodologies we look to for inspiration, in the way we consider our 'findings' and what we think they mean, our values are present.

This realization has reshaped my understanding of research. Every choice in the research process, from the questions I ask to the way I interpret data, is deeply intertwined with normative commitments. Recognizing this has not only made me more conscious of the values driving my work but also more critical of the research I engage with. Acknowledging the normative dimensions of my research has also led to a greater appreciation of the complexity of the research process. Each of the environmental and urban, have social and political dimensions layered and intertwined with their biological and technical characteristics.

5.1.3 Only the direction matters

Urban and environmental studies are, by their very nature, interdisciplinary endeavors. The complexity of urban systems demands insights from a wide range of disciplines. Similarly, environmental challenges cut across traditional academic boundaries.

This inherent interdisciplinarity presents both opportunities and challenges. It offers the potential for rich, multifaceted understandings of urban sustainability issues. It also requires navigating diverse epistemologies, methodologies, and disciplinary cultures. I have come to appreciate that true interdisciplinarity goes beyond merely combining methods or data from different fields. It requires a fundamental rethinking of how we frame research questions, conduct analyses, and interpret results.

In this context the process of coming to better understandings of urban environmental issues is often more important than those understandings themselves. Even if some aspects of urban environmental challenges can to some degree be described by immutable laws of physics, the dynamic nature of urban environmental challenges suggests the meaning, value, importance of these laws need to be considered and reconsidered over time.

This orientation toward process suggests that in urban environmental research, the direction of our investigations matters more than their pace. While urban challenges demand urgent responses, hasty or misguided trajectories can lead to unintended consequences that may worsen the very problems we seek to solve. What matters most is ensuring our research moves steadily toward more sophisticated and inclusive understandings, even if this sometimes means proceeding more slowly than the pressing nature of urban environmental challenges might seem to demand.

5.2 Limitations

The research presented in Chapters 2-4 of this thesis, while offering insights into empirical urbanism, is subject to several overarching limitations. Some of these limitations are specific to a chapter while others cut across chapters. These limitations stem primarily from the methodological approach employed, which, while effective in critiquing positivist methods, itself relies heavily on positivist and post-positivist paradigms. This 'critique-through-practice' approach, while illuminating certain shortcomings of science of cities literature, and in cases of wider empirical urbanism, may inadvertently reinforce the primacy of quantitative, data-driven methodologies in urban studies. Furthermore, the studies' reliance on statistical analyses and economic frameworks, though effective in their respective contexts, may not fully capture the complex, qualitative aspects of urban phenomena and the sociopolitical implications of data use in urban planning and governance.

These thematic limitations extend to the lack of integration of alternative theoretical frameworks, the potential benefits of greater methodological pluralism, and the need for deeper exploration of epistemological tensions within urban studies. Each chapter, whether focusing on big data, data scaling, or the co-benefits of climate action, could have benefited from incorporating perspectives from critical data studies, assemblage theory, or environmental justice frameworks. Additionally, the research process might have been enriched by more extensive use of qualitative methods, such as interviews, ethnographic observation, or participatory research. Finally, a more explicit examination of my own positionality and potential biases, stemming from a background in the natural and economic sciences, could have provided valuable context for interpreting the findings and their implications for urban studies and practice.

5.2.1 Big Data: Fair Weather Forecasting? The Shortcomings of Google Maps for Transport Planning, a case study from Huballi-Dharwad, India

Reflecting on the study of Google Maps data for urban transport planning in Huballi-Dharwad, I recognize both some innovative aspects and several limitations. Specific limitations in the analysis include restricting the data collection from mid July 2018 to Tuesdays and Thursdays. This change, brought about by changes in the cost of accessing Google maps API, may have limited our insight into changes in the transport system over this period. Tuesdays and Thursday were chosen because they capture commuting for work, a major part of transport demand, and avoid holidays and other unique disruptions affecting other days of the week during this period.

More generally, the research methodology, while aiming to critique data-driven techniques, paradoxically employs similar quantitative methods, potentially reinforcing their dominance in urban studies. This approach, rooted in statistical comparisons, effectively highlights certain shortcomings of big data but may not fully capture the nuanced qualitative limitations of such approaches in complex urban contexts. I now see that this methodological choice may have inadvertently overlooked crucial sociopolitical implications of big data use in urban planning.

In hindsight, the study could have been strengthened by integrating alternative theoretical frameworks, such as critical data studies or science and technology studies. These perspectives could have provided deeper insights into the implications of big data in urban contexts, moving beyond mere quantitative analysis. The absence of qualitative methods, including interviews with urban planners or ethnographic observations of data use in practice, now appears as a missed opportunity to enrich the critique. Additionally, I recognize that a more explicit exploration of the epistemological tensions between positivist assumptions of objective data and interpretive approaches viewing data as socially constructed could have added valuable depth to the analysis.

Reflecting on my own positionality, I realize that my background in quantitative methods likely influenced my initial approach to this research. While this background provided valuable skills for data analysis, it may have also led to an overreliance on statistical methods at the expense of more diverse analytical approaches. Moving forward, I am committed to broadening my methodological toolkit and engaging more deeply with qualitative and critical approaches to develop a more comprehensive understanding of the complex interactions between big data, urban planning, and sociopolitical contexts.

Chapter 2 also highlighted key boundaries of conventional academic partnerships. The research team's shared quantitative orientation enabled sophisticated analysis of Google Maps data but also revealed our collective epistemological blind spots. The team brought together expertise in transport planning, urban development and economics, fields that share broadly similar empirical methods and positivist underpinnings. However, our inability to fully explain or account for the data gaps discovered in informal settlements and during extreme weather events pointed to the need for knowledge that lay beyond our combined expertise. Fieldwork in Huballi-Dharward made this limitation particularly apparent - while we could identify biases in the data through statistical analysis, we lacked the methodological tools and epistemological frameworks to meaningfully engage with the lived realities these biases represented. This realization contributed significantly to my evolving understanding of interdisciplinarity as requiring not just collaboration across academic disciplines, but engagement with fundamentally different ways of knowing. The experience of completing Chapter 2 thus played an important role in developing the argument I will be putting forward for more transformative approaches to interdisciplinary urban environmental research later in this section.

5.2.2 New Methods: Data Scaling: Implications for Climate Action and Governance in the UK

Chapter 3 explores the intersection of methodological choices and climate action priorities through analysis of greenhouse gas emissions data at different scales. While the research effectively demonstrates how data analysis methods can systematically affect policy priorities - showing that focusing on local rather than national priorities could increase emissions coverage by up to 35% - it also reveals limitations in conventional approaches to academic knowledge production. The single-authored, empirically-focused nature of the research enabled detailed statistical analysis but constrained engagement with how different forms of knowledge about emissions and climate priorities emerge through collaboration between actors working at different scales.

The methodological framework contains several technical limitations. The analysis compares how sources of emissions rank between places, treating each source as a potential 'sector' for intervention, but the language used to describe this approach was at times misleading. The text could have been clearer, for example, that the analysis examines emissions rankings rather than climate action plans. Similarly, the description of how emissions coverage changes under different prioritization schemes required more detailed explanation of how key percentages were derived - specifically that these values emerge from comparing the share of emissions covered by the largest three local sources versus the three sectors that are largest nationally.

Limitations of the methodological framework were also aggravated by a lack of examples, and a more detailed and clear explanation of the approach. The text could have explained in more detail, for example, that the analysis does not look at climate action plans. Instead, the analysis looks at sources of emissions in two datasets compares how those sources of emissions rank (from largest to smallest) between places and understands each of these sources of emissions as a potential ‘sector’ for intervention. This use of language was misleading.

A second example where the language of the paper could have been improved is in the description of how the coverage of climate action plans would change if different numbers of sectors (emission sources) were covered. The text, for example, notes that “if three sources of emissions are considered, focusing on the priorities specific to each LSOA increases the coverage of a climate action plan by 28-35%” (p.55). What should have been made clear in the text is that these percentages are the derived from dividing the share of emissions covered by the largest three local sources of emissions by the share of local emissions covered by the three sectors that are largest nationally. When half of sectors are considered that includes six sectors.

The analysis should also have provided discussion of the correlation between the difference between local and national prioritisation and the multiple index of deprivation. The correlations with each dataset, one covering territorial emissions and the other consumption emissions, are very low, 0.11 and 0.08 respectively. What should have been highlighted is that these minor correlations may still provide insight given the scale of potential welfare and equity implications of climate action. Should the correlation have been statistically insignificant we could not have made this claim.

More fundamentally, while the analysis reveals that data scaling might disproportionately affect areas facing higher levels of deprivation (with correlations of 0.11 and 0.08 between scaling effects and deprivation for territorial and consumption emissions respectively), it does not explore how this knowledge might be understood and acted upon differently by various stakeholders. A more collaborative approach involving researchers and practitioners working at different scales could have provided insight into how priorities are set at different scales, how conflicts between local and national priorities are resolved in practice, and how data analysis methods interact with institutional and political processes.

Alternative theoretical frameworks could have helped address these limitations. Actor-network theory could have provided a framework for understanding how different forms of knowledge about emissions are produced and validated across governance scales. Assemblage theory could have revealed how methodological choices interact with institutional arrangements and power relations to shape climate priorities. These theoretical perspectives, combined with qualitative methods such as case studies or discourse analysis, could have situated the statistical findings within broader social and political contexts.

The experience of conducting this research played an important role in developing the understanding of interdisciplinarity presented in this thesis. Identifying important patterns in how we understand climate priorities while simultaneously recognizing the inadequacy of purely empirical approaches to fully explain these patterns helped reveal the need for more transformative approaches to knowledge production. This understanding builds on insights from Chapter 2 about the limitations of Big Data approaches and anticipates Chapter 4's explicit engagement with normative assumptions in empirical work.

5.2.3 New Methodologies: The Hidden Social Value of Achieving the UK's Climate Targets

The study on the co-benefits of climate action, while comprehensive in its economic analysis, faces limitations in its framing and methodological approach. The economic framing of co-benefits, although critiquing narrow financial analyses, still operates within a quantitative, positivist paradigm. This approach might miss important qualitative aspects of climate action benefits and may not fully capture the complex social and cultural dimensions of urban sustainability initiatives.

The research could have been enhanced by integrating alternative frameworks, such as environmental justice or capabilities approaches, to provide a richer understanding of the distribution and nature of climate action benefits. The use of participatory research methods to understand how communities perceive and value co-benefits could have added depth to the economic analysis. Furthermore, a more explicit examination of the epistemological assumptions behind quantifying social benefits, and how these might conflict with more interpretive or critical approaches to understanding social value, would have strengthened the study's theoretical foundation.

The development of Chapter 4 marks an important stage in the evolution from conventional to transformative interdisciplinarity traced in this thesis. While the research successfully integrated economic and social analysis, enabling sophisticated modeling of co-benefits, it remained constrained by shared epistemological assumptions about what constitutes valid knowledge. This limitation - visible in the systematic exclusion of forms of social value that resist economic quantification - helped reveal the need for research approaches that could engage with different ways of knowing. The experience contributed significantly to the understanding developed in this conclusion that meaningful interdisciplinarity requires not just collaboration across disciplines but engagement across deeper epistemological divides.

5.3 Key Findings: Roadblocks to a Coherent Quantitative Environmental Urbanism?

Overflowing optimism (Folke et al., 2016; Grimm et al., 2015; McPhearson et al., 2016; Meerow et al., 2016; Creutzig 2019) but also deep scepticism (Brenner & Schmid, 2015; Westman & Castán Broto, 2022), characterise perspectives around the value of contemporary quantitative urban environmental literature. Cutting through these perspectives to understand in detail how a quantitative urbanism in its modern form is challenged as it engages with urban environmental challenges is critically important to orienting research towards the questions that can most rapidly advance urban environmental knowledge.

To understand the contribution of this field to the urban environmental field I start by considering each chapter (each of which focuses on a characterising feature of contemporary quantitative urban environmental literature) and follow by thinking thematically across the chatpters.

5.3.1 Chapter 2: Fair Weather Forecasting? The Shortcomings of Google Maps for Transport Planning, a case study from Huballi-Dharwad, India

Chapter 2 presents an analysis of the transport network in Huballi-Dharward, India, using data collected from Google Maps. The study finds that while the Big Data source explored can provide insights into traffic patterns and the impact of new infrastructure, it fails to capture critical events like flooding and shows potential bias in data quality between slum and non-slum areas. These specific issues echo concerns raised by scholars such as Kwan (2018), who warns of systematic biases in Big Data sets, and Nagendra et al. (2018), who highlight how urban data often fails to adequately represent marginalized populations. The inability of Google Maps data to reflect the impact of major flooding aligns with Kitchin et al.'s (2015) caution about the limitations of real-time urban data for capturing complex urban dynamics.

These data-specific problems also point to deeper epistemological issues that may be inherent in the use of Big Data for urban analysis. The lack of transparency in data collection, cleaning, and presentation processes creates a "garden of forking paths" where the extent of biases and blindspots becomes impossible to ascertain fully challenging our ability to critically evaluate the knowledge produced through such data (Gelman and Loken 2014). The application of this data to urban topics that are already challenging to operationalize, such as mobility patterns in informal settlements, risks what Yarkoni and Westfall (2017) describe as the conflation of measurement with understanding. Without a clear grasp of the data's limitations, researchers may draw conclusions that appear robust but are built on shaky epistemological foundations.

Overarching these issues is the question of embedded political and normative considerations within the data itself. As Gleeson (2014) and Brenner (2015) argue that seemingly neutral data can often embody and perpetuate specific political ideologies or normative assumptions about urban life. In the case of Google Maps data, the very choice of what to measure and how to present it may reflect particular views about what constitutes important urban mobility, potentially sidelining other perspectives. This case study thus underscores the need for a more reflexive and critical approach to empirical urban analysis, one that acknowledges the limitations and potential biases of Big Data sources and seeks to integrate them with other forms of urban knowledge. It calls for greater transparency in data methodologies and a more nuanced understanding of the relationship between data, knowledge, and urban realities.

5.3.2 Chapter 3: Data Scaling: Implications for Climate Action and Governance in the UK

Chapter 3 explores the implications of data scaling for climate action and governance in the UK, focusing on how the aggregation of greenhouse gas emissions data at different geographic levels can affect climate policy priorities. The study demonstrating that the way data is aggregated and analysed can significantly influence the perceived priorities for climate action between national and local levels. Results show that climate action plans developed at the local level could potentially cover up to 35% more emissions than those developed at the national level, due to the effects of data scaling. The chapter also finds a correlation between socio-economic deprivation and the degree of misalignment between national and local climate action priorities.

Chapter 3's analysis of data scaling in climate action planning offers an extension of the challenges raised in Chapters 1 and 2, while providing new insights into the role of data and quantitative methodologies in urban environmental governance. Unlike the opaque data sources examined in Chapter 2, Chapter 3 deals with known data sources and transparent analytical processes, offering a different lens through which to view the issues of procedural flexibility and embedded values in empirical urban analysis. This transparency in data sources and methods illuminates a critical insight: even when processes of analysis are carefully considered and documented, the very nature of empirical methods can still significantly affect our understanding of urban environmental challenges. This finding extends beyond Gelman and Loken's (2014) "garden of forking paths" concept, suggesting that procedural transparency, while necessary, is not sufficient to fully address the epistemological challenges in urban data analysis. This aligns with recent work demonstrating that urban sustainability outcomes are sensitively dependent on wider global systems, highlighting the need for multi-scale integrated assessment approaches (Purvis et al., 2022).

In addition, Chapter 3 presents an alternative perspective on how political and normative considerations become embedded in empirical analysis. Where Chapter 2 highlighted how choices in data collection and analysis can explicitly (if indirectly) reflect the values and positions of organizations involved in Big Data generation, Chapter 3 demonstrates how even a relatively simplistic and transparent set of methods can become a vehicle for opposing perspectives. This is particularly evident in how data scaling affects the prioritization of climate actions at different governmental levels, potentially leading to divergent policy focuses despite using the same underlying data.

These findings have particular relevance for the growing body of literature on locally-led and 'place-based' approaches to climate action, such as those discussed by Howarth et al (2020). The push for localized climate strategies, while valuable for addressing context-specific needs, may also be influenced by the very ways in which local data is analyzed and interpreted. This raises important questions about how to balance local insights with broader regional or national priorities in climate governance.

In these ways Chapter 3 demonstrates that the challenges of empirical urban analysis extend beyond issues of data quality or bias to encompass the very ways in which we structure and interpret our analyses. As urban environmental governance increasingly relies on data-driven decision-making, understanding and accounting for these methodological effects becomes crucial for developing effective, equitable, and truly place-responsive urban policies.

Chapter 3 thus underscores the need for a more reflexive approach to urban data analysis, one that goes beyond ensuring methodological transparency to actively consider how analytical choices might shape our understanding of urban challenges. Achieving more active integration of data analysis with domain-specific knowledge in urban planning and environmental governance echoes McPhearson et al.'s (2016) call for more interdisciplinary approaches in urban science.

5.3.3 Chapter 4: The Hidden Social Value of Achieving the UK's Climate Targets

Chapter 4 presents an evaluation of the costs and benefits of climate change interventions in six urban regions of the UK, encompassing financial, social, and carbon dimensions. The study finds that meeting the UK's 2033-2037 climate targets could yield £164 billion in total benefits, with a striking 79% of these benefits being social in nature, including improvements in public health, reduced traffic congestion, and increased thermal comfort in homes. Notably, the analysis reveals significant variations in the scale and nature of benefits across different urban regions, highlighting the importance of place-specific approaches to climate action. The chapter also demonstrates the sensitivity of social benefits to normative decisions in empirical analysis, particularly in areas like transport emissions reduction strategies.

Chapter 4's comprehensive evaluation of climate change interventions in UK urban regions exemplifies and extends several key challenges and debates raised in the preceding chapters, particularly regarding the role of value-based decisions in empirical urban environmental analysis.

This chapter demonstrates how specific value-based decisions are deeply embedded in empirical analysis, a concern initially raised in Chapter 1's discussion of the challenges facing positivist approaches to urban questions. The stark variations in the scale and nature of benefits across different urban regions, and the sensitivity of social benefits to normative decisions, underscore what Gelman (2019) describes as the inextricable link between facts and values in social scientific research. The interdisciplinary nature of urban environmental studies, as highlighted by authors like McPhearson et al. (2016) is also highlighted by the importance of methodological choices related to the scope of the study. For instance, the chapter's finding that 79% of the benefits from climate actions are social in nature raises important questions about how we define and measure 'benefit' in urban environmental contexts.

The varying interpretations of social value observed in this case study also reflect what Winkler and Duminy (2014) describe as the need for meta-ethical examination in planning - understanding how different actors interpret ethical concepts rather than assuming shared meanings. This suggests that advancing urban environmental knowledge requires not just better methods or data, but deeper engagement with how foundational concepts are understood differently across contexts and stakeholders.

Building on the insights from Chapters 2 and 3, Chapter 4 takes the discussion of methodological transparency and reflexivity a step further. Where Chapter 2 demonstrated the need for making data analysis methods visible, and Chapter 3 highlighted the importance of actively considering how analytical choices shape narratives, Chapter 4 suggests that specific value-based choices and their effects need to be brought to the forefront of empirical analysis.

This shift in focus aligns with what Yarkoni (2022) calls for in terms of greater methodological transparency, but goes beyond mere disclosure or the championing of interdisciplinarity. It suggests that understanding where and how value-based decisions are made may, in some cases, be the primary purpose of empirical analysis. This is particularly relevant in urban environmental studies, where the complex interplay of social, economic, and ecological factors makes purely 'objective' analysis virtually impossible.

The chapter's findings on the variation of co-benefits across urban regions also extend the discussion on place-specificity raised in Chapter 3. It suggests that not only do analytical methods need to be sensitive to local contexts, but the very framework for evaluating outcomes needs to be flexible enough to capture place-specific values and priorities. Chapter 4's approach to quantifying and comparing different types of benefits (financial, social, and carbon) offers a practical example of how researchers might make value judgments more explicit in their analyses. By presenting these different dimensions side by side, the chapter invites readers to consider the trade-offs and value judgments inherent in prioritizing one type of benefit over another.

Chapter 4 thus pushes us to reconsider the role of empirical analysis in urban environmental studies. Rather than striving for a purely objective assessment, which the chapter suggests may be unattainable, it proposes a more nuanced approach that acknowledges and explicitly engages with the value-based decisions inherent in such analyses.This approach has significant implications for urban environmental governance. It suggests that policymakers and researchers need to be more explicit about the values driving their analyses and decision-making processes. It also highlights the need for more participatory approaches to urban environmental planning, where diverse stakeholders can engage with and influence the value judgments that shape empirical analyses.

Chapter 4 thereby exemplifies the challenges of value-laden decisions in empirical urban analysis but also points towards a more reflexive, transparent and active approach to urban environmental research. By bringing these value-based decisions to the forefront, it opens up new possibilities for more inclusive, context-sensitive, and ultimately more effective urban environmental governance.

5.4 Reflecting on the Key Findings of this Thesis: Towards a Reflexive Quantitative Urban Science

The findings across Chapters 2, 3, and 4 collectively point towards a need for quantitative urban environmental research that recognizes the complex interplay of social, ecological, and technological aspects of urban environments. Chapter 2's exploration of Google Maps data in Huballi-Dharwad demonstrates the challenges big data face capturing complex urban realities, such as the impact of flooding or the nuances of mobility in informal settlements. This underscores the need for diverse data sources and methodologies to comprehensively understand urban phenomena. Chapter 3 builds on this by revealing how different scales of analysis can lead to divergent policy priorities, highlighting the importance of integrating local and national perspectives. Chapter 4 further extends this call for pluralism by showing how the assessment of climate action requires the integration of financial, social, and environmental considerations, each typically the domain of different disciplines.

The evolution from conventional to transformative interdisciplinarity traced in this thesis reflects a growing recognition of the epistemological challenges facing urban environmental research. Beginning with relatively straightforward cross-disciplinary collaboration in Chapter 2, combining transport planning and economic analysis, the research progressively revealed the limitations of working solely within positivist frameworks. The discovery that key aspects of urban life systematically eluded quantitative analysis, despite sophisticated technical approaches, pointed towards the need for different forms of knowledge. This understanding deepened through Chapter 3's exploration of data scaling effects and Chapter 4's examination of embedded normative assumptions in empirical work. The vision for interdisciplinarity presented in this conclusion thus emerges from direct engagement with the boundaries encountered in conducting this research. While in some cases these limitations are explicitly highlighted in the academic paprts

This thesis charts both a conscious and unconscious evolution in understanding interdisciplinary urban research. While some insights, particularly around normative assumptions in Chapter 4, were explicit aims of the research, others emerged only through subsequent reflection. The significance of contextual sensitivity, evident in findings across all chapters, was not theoretically articulated during the original studies. Similarly, the value of epistemological tensions as catalysts for innovation only became apparent during synthesis of the research. This suggests that advancing interdisciplinary urban environmental research requires both empirical work and sustained critical reflection on research practices.

The chapters of this thesis also collectively suggest that a simple combination of disciplinary perspectives is insufficient. Instead, they point towards a more nuanced and reflective form of interdisciplinarity, characterized by several key features.

Firstly, these chapters highlight the need for contextual sensitivity. From the place-specific variations in data quality (Chapter 2) to the divergence between national and local climate action priorities (Chapter 3) and the varying co-benefits of climate interventions across urban regions (Chapter 4), the research consistently demonstrates that urban environmental challenges are deeply context-dependent. The development of place-responsive methodologies that can integrate scientific data with local knowledge is therefore suggested to be foundational to the advance of empirical urban research.

Secondly, these chapters highlight the need for active and engaged transparency in both methodological decisions and normative assumptions. The extent to which assumptions made during the modelling process seem to affect what data can tell researchers in Chapter 2, the significant impact of data scaling choices shown in Chapter 3, and the influence of value-based decisions on benefit assessments demonstrated in Chapter 4 all highlight the crucial importance of making explicit the methodological choices and value judgments that shape research outcomes.

Thirdly, these chapters highlight that productive tensions and epistemological conflicts are not a challenge to urban environmental research, but are in fact essential to its advancement. Rather than seeking to smooth over or resolve these tensions, embracing them as catalysts for deeper understanding and innovation may be key to advancing urban environmental knowledge. In Chapter 2, the study of Google Maps data in Huballi-Dharwad, India, reveals tensions between big data approaches and local contextual realities. Chapter 3's exploration of data scaling effects in UK climate action planning brings to light potential tensions between national and local perspectives. In Chapter 4, the assessment of the social value of UK climate targets reveals tensions between different conceptions of value in urban interventions. By bringing forward these tensions, each study demonstrates how a more holistic understanding of urban climate action can emerge.

A reflexively critical approach underpins each of these crosscutting findings. The emphasis on contextual sensitivity stems from a critical reflection on the limitations of universalist approaches to urban environmental challenges. The call for transparency in methodological decisions and normative assumptions arises from a reflexive examination of how research practices shape outcomes. The recognition of productive tensions as essential to advancing knowledge emerges from a critical engagement with the complexities and contradictions inherent in urban environmental issues.

This reflexive criticality is not just a methodological stance, but a fundamental orientation towards knowledge production in urban environmental research. It involves a constant process of questioning not just the subject of study, but also the methods, assumptions, and implications of the research itself. This approach recognizes that researchers are not neutral observers, but active participants in shaping understandings of urban environments.

This reflexively critical approach to urban environmental research is inherently interdisciplinary, not because it combines different disciplinary perspectives, but because it recognizes that understanding urban environments requires transcending traditional disciplinary boundaries. The integration of contextual sensitivity, methodological transparency, and productive tensions demands engagement across epistemological divides. Such integration cannot be achieved through simple methodological pluralism, but requires a fundamental rethinking of how we produce knowledge about urban environments. This approach offers a path toward urban environmental research that is both more coherent and more honest about the complexities of knowledge production in urban contexts.

Each of the claims I make above are found in existing literature. The combination of these claims, however, and a focus on these elements over others for realising a quantitative environmental urbanism that supports a more interdisciplinary urban environmental field marks this thesis as unique. In the following section, I will explore how the reflexively critical approach suggested here both conflicts with and complements existing calls for interdisciplinarity in urban environmental empirical literature.

5.5 Reflecting on Existing Calls for a more Interdisciplinary Quantitative Urbanism

Scholars from have long recognized the complex, multifaceted nature of urban environmental challenges and the need for integrated approaches. Ambiguity in the theoretical foundations of sustainability frameworks, as highlighted by Purvis et al. (2019), for example, underscore the need for more rigorous conceptual work in empirical urban environmental research. This section will examine how the key findings of this thesis complement and conflict with existing calls for a more interdisciplinary urban environmental research.

5.5.1 Contextual sensitivity: Are We Forgetting Replicability?

A need for contextual sensitivity is a prominent theme across the work of authors calling for a more interdisciplinary urban subject (c.f Acuto et al., 2018; Creutzig et al., 2024; Groffman et al., 2017; McPhearson et al., 2016; Solecki et al., 2013). Acuto et al. (2018) and Creutzig et al. (2024), for example, make the case for urban science to seek "generalizable insights" while maintaining local contextual validity. McPhearson et al. (2016), state that urban research must "investigate multiple spatial and temporal scales, as well as cross-scale interactions" built around the knowledge of local stakeholders (p.203).

Generalising urban knowledge is essential for realising action on climate change as well as a host of other social, environmental and economic challenges. Less emphasied in these papers, and equally essential, is the role of contextual specificity for understanding how places are unique. Knowing when ideas, concepts, scientific laws, methodologies, exist within and across all cities is no less important than knowing when and where each of these might need to be significantly adapted or changed to meet a local context.

This distinction is between 'generalisability' and 'replication' (Sudmant, Creutzig and Mi 2024). Replication narrowly is the challenge of reproducing a study's findings. More broadly, replication as a concept engages with the challenge of applying empirical epistemologies to urban concepts that are qualitative, poorly defined, and / or complex. Such concepts include the quality of urban governance, social capital, sense of place, urban identity, neighbourhood character, the right to the city, community cohesion, and civic engagement. Generalisability, by contrast is the challenge of understanding when and where concepts in a specific context offer insights in other urban contexts.

Chapter 2 did not explicitly mention replication or generalisability. However, the conclusion that urban mobility in Huballi-Dharwad may not be well understood using Big Data from Google and could be improved if it were complemented by wider methods of knowledge generation suggests that Big Data approaches to understanding urban mobility may face challenges generalising across urban areas. It also suggests that replicating a study that engages with ‘urban mobility’, or comparing two studies that both consider urban mobility, will require engaging in detail with place-based operationalisations of the concept.

Replication and generalizability can complement each other in urban research, serving as conceptual scaffolds to support the translation of methodologies, findings, and theories between disciplines. Successful replication of a study across multiple cities can contribute to the generalizability of its findings, while attempts to generalize findings can reveal the need for better replication strategies to account for the different ways urban concepts are understood in different urban contexts (Sudmant, Creutzig and Mi 2024).

Confusing these concepts can lead to consequences, however, including the overextension of findings to inappropriate contexts, neglect of crucial local specificities, and misinterpretation of research limitations. When we confuse replicability with generalizability, we may incorrectly assume that a study's findings are applicable across diverse urban settings. Conversely, when we confuse generalizability with replicability, we may mistakenly believe that a finding which appears to hold true across various urban contexts can be easily reproduced in a specific context. Arguably of greatest importance in calls for the development of interdisciplinarity is therefore the need to distinguish between these concepts and the role they can play advancing more coherent research (Sudmant, Creutzig and Mi 2024).

5.5.2 Active and engaged transparency: From Epistemic to Epistemological Transparency?

Calls for the development of a more interdisciplinary urban research increasingly recognize the importance of transparency (Acuto et al., 2018; Creutzig et al., 2024; Groffman et al., 2017; McPhearson et al., 2016; Solecki et al., 2013), yet the depth and breadth of this transparency vary. Authors such as Creutzig et al. (2024), Acuto et al. (2018), Groffman et al. (2017), and Solecki et al. (2013) advocate for greater openness in research practices, focusing primarily on epistemic transparency - a form of methodological clarity that allows for understanding, evaluation, and the replication of research.

This emphasis on epistemic transparency, while valuable, often fails to address the full spectrum of assumptions and value judgments underpinning urban environmental research. Calls for participatory approaches, new intellectual networks and conceptual synthesis (Acuto et al., 2018; Creutzig et al., 2024; Groffman et al., 2017) hint at the need for a more comprehensive form of transparency, but do not explicitly advocate for researchers to articulate and critically examine their normative positions.

The limitations of this purely epistemic transparency are particularly acute in urban climate change research, where complex socio-ecological systems intersect with urgent policy needs. As climate action increasingly focuses on cities, there is a need to move beyond questions of 'how we know' to 'what we should do with what we know'. In other words, moving from epistemic to epistemological transparency requires examining not just how we know, but how we understand and interpret ethical concepts themselves. This meta-ethical dimension of transparency, as highlighted by Winkler and Duminy (2016) involves making explicit how different actors interpret and assign meaning to foundational concepts like 'improvement,' 'benefit,' or 'progress' rather than assuming shared understanding.

Epistemological transparency is crucial for bridging divides between natural and social sciences, fostering interdisciplinary collaboration by creating a common ground for understanding diverse research paradigms. It acknowledges the inherently normative nature of urban environmental research and its potential to shape urban futures. By surfacing value-based decisions in research design, data interpretation, and policy recommendations, epistemological transparency allows for a more honest dialogue about the role of science in addressing urban climate challenges. Recent work on reconciling different forms of urban knowledge provides a framework for achieving epistemological transparency. Hong et al. (2023) propose a three-stage process of integration spanning research formulation, data collection/analysis, and knowledge representation. This 'reconciliatory process' recognizes that tensions between different approaches can be productive rather than problematic

Actively engaging with the implications of research choices and fostering open dialogue about the values underlying urban research is a necessary step towards producing more reflexive, ethically grounded, and societally relevant research. By rejecting the notion that empirical urban environmental research can be purely objective, and instead embracing the interplay of facts and values, we can develop research practices better equipped to address the multifaceted challenges of urban climate change. This shift from epistemic to epistemological transparency represents a crucial evolution in urban environmental research, aligning more closely with the complex, value-laden nature of the urban systems we study and seek to influence.

5.5.3 Productive tensions and epistemological conflicts : Are boundary objects the answer?

The notion that productive tensions and epistemological conflicts are key to advancing urban environmental reseacher finds some support across calls for a more interdisciplinary urban environmental subject. Creutzig et al. (2024) and McPhearson et al. (2016) argue for interdisciplinary approaches that are not embedded in any single disciplinary perspective. Groffman et al. (2017) similarly advocate for integration across academic disciplines and professional practices, recognizing the value of diverse perspectives in urban research. Solecki et al. (2013) and Acuto et al. (2018) call for a science of urbanization that draws from multiple disciplines.

These approaches undoubtably lead to the surfacing of epistemological tensions even if this purpose is not explicitly highlighted. An explicit purpose of surfacing these tensions, and suggestions for the means of surface these tensions, however, are lacking in these literature. McPhearson et al (2015) and Groffman et al (2016), for example, describe an interdisciplinary science of cities explicitly emerging from urban ecology. Such an approach would embed the languages, norms, perspectives and approaches of urban ecology in a new science, potentially crowding out those of other fields.

Implicitly acknowledging the irony of building an interdisciplinary subject on a foundation of a single field, Creutzig et al (2024) proposes a different approach. Defining four kinds of knowledge (process, orientation, transformation and system), Creutzig et al (2024) provides a theory of change for the urban environmental subject that they describe as leading to a more interdisciplinary and action-oriented field. Problematically, such an approach potentially replaces existing disciplinary silos with new ones. Whose knowledge is process related and which field would like to cede their work as not being about the 'system'? If all of our areas of expertise include all of these kinds of knowledge, how does a conceptualisation of interdisciplinary developed around the interactions *between* rather than within those knowledges, advance productive interactions between different understandings of these knowledges?

The fundamental challenge being faced is the paradox of commensurability (Cartwright, 1999). Some level of commensurability is necessary for any meaningful exchange across disciplines. And yet strong commensurability, a defined understanding of concepts as proposed by McPhearson et al (2015) and Groffman et al (2016), or a prescribed framework for interaction as suggested by Creutzig et al (2024), risks diminishing the very diversity and richness of perspectives that interdisciplinarity seeks to harness.

The challenge, therefore, is to foster interdisciplinary exchange without imposing a rigid framework that undermines the very diversity it seeks to leverage. One promising approach lies in the concept of "boundary objects," as developed by Star and Griesemer (1989). Boundary objects are entities that inhabit multiple social worlds and facilitate communication between them, allowing for collaboration without consensus. In the context of urban environmental research, concepts like "sustainability," "resilience," and "urban metabolism" could serve as boundary objects, flexible enough to be interpreted through various disciplinary lenses while providing a common point of reference.

5.6 A Roadmap for developing a more coherent quantitative environmental urbanism

The findings of this thesis, alongside a body of literature calling for an integrated urban environmental subject (Acuto et al., 2018; Creutzig et al., 2024; Groffman et al., 2017; McPhearson et al., 2016; Solecki et al., 2013), point towards several critical areas for future research. This section outlines a roadmap for advancing our understanding of urban environmental challenges. By focusing on these areas we can work towards a more coherent and impactful urban environmental science that is better equipped to address the complex challenges facing cities in the 21st century.

5.6.1 Deepening of Our Understanding of Replication and Generalizability in Urban Environmental Research

Replication and generalisability have been suggested as boundary objects that may play an important role helping to develop a more interdisciplinary urban environmental literature (Sudmant, Creutzig, Mi, 2024). As discussed in 5.4.1, these boundary objects could play an important role helping to orient the role of context in urban environmental research – towards understanding the unique aspects of places (replication) or towards understanding what places have in common (generalisability).

Studies focusing on replication in urban contexts are essential for unpacking the fundamental characteristics of the urban. Such research should critically examine which phenomena are inherently urban and which are merely applications of broader processes to urban settings. This line of inquiry can help refine our operationalization of key urban concepts and clarify the boundaries of urban studies. The challenge of replication has been present in urban debates for decades, as evidenced by early critiques of systems theorists in the 1950s and 1960s (Batty, 2012b) and later criticisms of quantitative urbanism for ignoring underlying social and economic processes (Healey, 1987). More recently, critiques of Big Data urbanism (Brenner & Schmid, 2015; Gleeson, 2014) have highlighted ongoing replication challenges.

Generalizability-focused research is equally crucial, addressing when and how urban insights can be meaningfully applied across different contexts. This work is supported by the development of frameworks for understanding how factors such as city size, economic structure, cultural context, and governance systems mediate the applicability of urban theories and findings between contexts. The longstanding debate over 'universalizing urbanism' (Robinson & Roy, 2016; Storper & Scott, 2016) reflects the persistent nature of generalizability concerns in urban studies. Earlier work by authors like Sayer (1984), Harvey (1992), and Olsson (1980) questioning how we understand information in urban analyses also speak to debate around generalisability.

Moreover, research exploring the complementarities between replication and generalizability is needed. This could involve developing mixed-method approaches that combine in-depth case studies with comparative analyses, or creating new analytical frameworks that explicitly address both the unique aspects of specific urban contexts and the broader patterns that emerge across cities. Such work could help reconcile the seemingly contradictory demands for both depth and breadth in urban research, a tension that has characterized urban studies for decades.

5.6.2 Harnessing Reflexivity

Reflexivity, as a methodological and epistemological stance, is crucial for advancing interdisciplinary urban environmental research. It allows researchers to critically examine their own assumptions, biases, and disciplinary perspectives, thereby contributing to contextual sensitivity, active and engaged transparency, and the cultivation of productive tensions. These three elements, in turn, can support the development of a more coherent and impactful interdisciplinary approach to urban environmental challenges.

The importance of reflexivity in fostering contextual sensitivity is exemplified by Middlemiss et al.'s (2023) person-centered approach to understanding Net Zero policy impacts. Reflexive framework encourage researchers and policymakers to consider how environmental initiatives affect people's lives holistically, rather than focusing on narrow sectoral impacts. In the context of this thesis, reflexivity facilitated a critical examination of big data limitations in urban transport planning (Chapter 2), highlighting the importance of local knowledge and context-specific factors that may be overlooked in large-scale data analyses.

Reflexivity also promotes active and engaged transparency by encouraging researchers to make explicit their underlying assumptions and value judgments. Blanchard (2012) demonstrates how reflexivity can reveal hidden assumptions and biases, leading to more nuanced understandings of urban systems. This was particularly evident in Chapter 4's examination of the hidden social value of climate interventions, where reflexive practices helped uncover implicit value judgments in cost-benefit analyses. Payne (2000) emphasizes that reflexivity is crucial for navigating the epistemological challenges that arise when integrating diverse disciplinary perspectives. In urban environmental research, where effective collaboration between natural scientists, social scientists, and urban planners is essential, this reflexive navigation becomes particularly important for bridging different knowledge systems and methodological approaches.

Reflexivity also plays a vital role supporting the cultivation of productive tensions and epistemological conflicts. Castan Broto (2020) show how reflexivity enables researchers to navigate the "messiness" of urban environmental questions that don't fit neatly into disciplinary boundaries. Van Veelen and van der Horst (2018) argue that concepts like energy democracy can serve as reflexive frameworks for integrating social and technical perspectives on urban transitions. Such frameworks can act as boundary objects, facilitating communication and collaboration across disciplinary divides while maintaining epistemological diversity.

Simon and Graybill (2010) highlight the difficulty of maintaining disciplinary identity while engaging in interdisciplinary work, a challenge that requires ongoing reflexive practice. Forino et al. (2024) point out that reflexivity can be time-consuming and may initially slow down research processes, which can be challenging in fast-paced urban research contexts. Despite these challenges, reflexivity presents significant opportunities for advancing urban environmental research.

Reflexivity also serves as a powerful tool for addressing power dynamics and ethical considerations in urban environmental research. By encouraging researchers to critically examine their own positionality and the broader sociopolitical context of their work, reflexive practices can help uncover and address potential biases and inequities in research design, data collection, and interpretation. This is particularly crucial in urban environmental studies, where research outcomes can have significant implications for diverse urban populations and ecosystems. Purvis's (2021) discussion of the potential for urban studies to engage critically and constructively with 'urban science' approaches exemplifies the kind of reflexive thinking needed to bridge different epistemological traditions in urban environmental research.

5.6.3 Cultivating Epistemological Conflicts: Boundary objects and trading zones as the way forward?

Epistemological conflicts can act as catalysts for innovation and deeper understanding. This perspective aligns with a growing body of literature that recognizes the productive potential of epistemological tensions in research. Barry (2008) for example, discusses the "agonistic-antagonistic" mode of engagement in interdisciplinary work, where conflict plays a generative role. Frodeman and Mitcham (2007) argue that productive tensions between disciplines can lead to more robust knowledge production. Castán Broto et al. (2019) emphasize the importance of embracing contradictions and tensions in urban sustainability research, implying that acknowledging epistemological conflicts can lead to more nuanced understandings of complex urban systems.

Boundary objects, as conceptualized by Star and Griesemer (1989) and further explored by Cuppen et al. (2021), may serve as a powerful means of cultivating epistemological conflict in a constructive manner. As entities that inhabit multiple social worlds and allow for translation between them, boundary objects can create spaces where different epistemologies can interact and clash productively.

The concept of boundary object ecologies extends this further by recognizing that boundary objects don't exist in isolation but form interconnected networks that co-evolve over time. As Cuppen et al. (2021) demonstrate, earlier boundary objects create the context that shapes how subsequent ones emerge and function - forming an ecological system of translations between different epistemological perspectives. In urban environmental research, such ecologies might include interconnected visualizations, models, frameworks and documentation that together enable sustained dialogue across disciplinary boundaries. The ecological perspective suggests that cultivating epistemological conflict requires attention not just to individual boundary objects, but to the broader system of interrelated objects that collectively enable translation between different ways of knowing. This systems view aligns with the inherent complexity of urban environmental challenges, which require sustained engagement across multiple knowledge domains.

The cultivation of productive tensions aligns with recent calls to reconcile different forms of urban knowledge generation. As Hong et al. (2023) argue that reconciliation becomes an interdisciplinary practice when different methodological approaches and insights are applied across the research process. This suggests the need to deliberately design research processes that surface and work through epistemological differences - not just at the analysis stage, but throughout the entire research journey from initial formulation through to knowledge representation. Similarly, the cultivation of productive tensions aligns with calls to move beyond unproductive critique of empirical approaches. As Duminy and Parnell (2020, p.653) argue, what is needed is "productive critique that expresses care for the subject," recognizing that urban sciences do not exist on :the far side of a fundamental rift." This suggests that epistemological conflicts can be generative when approached with genuine openness to different ways of knowing

Building on these ideas suggests that the deliberate design of participatory processes that foster the emergence of boundary objects may be an effective way to cultivate epistemological conflict. In the context of urban environmental research, boundary objects are particularly valuable due to the compound complexity of both urban systems and environmental issues. Cities are multifaceted entities encompassing social, technical, economic, and ecological dimensions, while environmental challenges like climate change involve complex interactions across scales, sectors and time. This complexity necessitates collaboration across disciplines, and boundary objects can provide a common ground for diverse experts to engage.

In conclusion, cultivating epistemological conflict through the creation of boundary object ecologies offers a promising path forward for urban environmental research. This approach embraces the complexity of urban systems while fostering the deep interdisciplinary collaboration necessary to address pressing urban sustainability challenges. Further research is needed to refine and validate this approach across different urban contexts and research domains, but I believe holds significant potential for advancing our understanding and management of complex urban environmental issues.

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6 Appendix 1

TABLE OF CONTENTS

6.1 Baseline carbon emissions

We set a baseline based on BEIS Energy and Emissions Projections (2020) being fully delivered under the existing arrangements, as well as policies that were published ahead of the release of the Government's Net Zero Strategy.

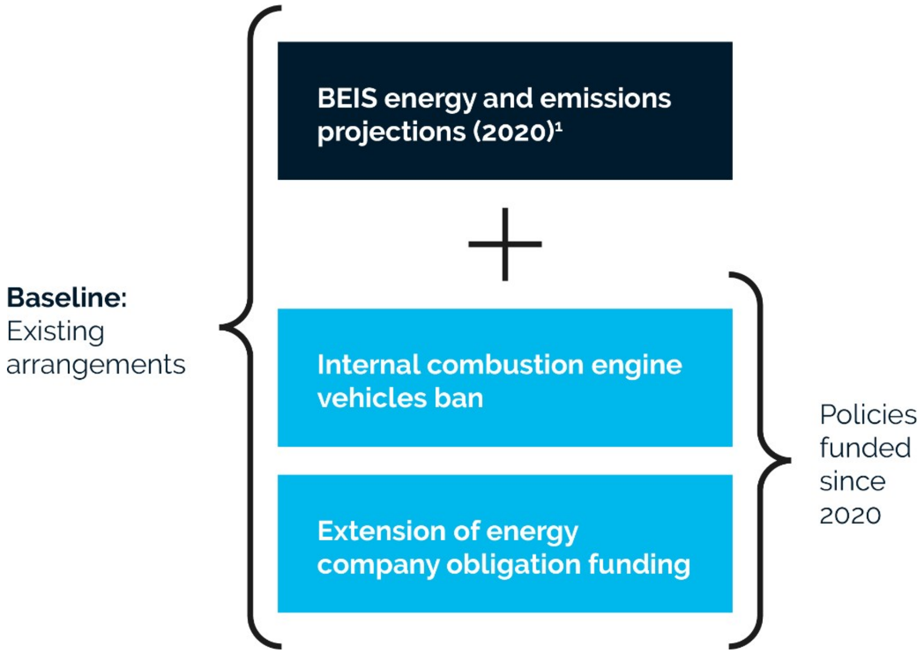

Figure 6-6-1: Representation of baseline methodology

The business-as-usual (BAU) trajectory for city-scale production-based (PB) emissions, i.e. the carbon emitted either directly within the city region's boundaries or indirectly via electricity use (Scope 1 and Scope 2 in GHG Protocol for Cities). Our focus was on all greenhouse gases measured as the mass of CO2e.

6.1.1 Emissions data sources

Our starting point was historical local authority carbon emissions data. To develop a BAU trajectory, we projected emissions forward by utilising city region-level population forecasts and national-level emissions scenarios:

- Local authority-level carbon emissions data disaggregated among domestic, industrial and commercial, and transport sectors and various sub sectors is available from The Department for Business, Energy and Industrial Strategy (BEIS). Time period covered: 2005–2018.
- Both UK- and LA-level population projections are regularly updated by the Office for National Statistics (ONS).
- UK-level projections of emissions and the carbon intensity of electricity supply are also available from BEIS, covering both CO2 and other GHGs and disaggregated by nine sectors. Time period covered: 1990–2040.

6.1.2 Emissions projections

To develop a forecast of BAU emissions, we first matched the BEIS national-level emitting sectors to the city region-level sectors, aggregating into clusters where necessary (see Table 1). Using these growth rates, we used the latest city region-level, per capita emissions for each sector and projected them forward to 2050. We therefore assumed that the per capita growth rates in emissions at the city region-level and national level are the same for each sector/cluster.

Table 6-1: National-level sectors from the BEIS emissions scenarios matched to the city region level, local authority emissions sectors

	National-level		City region-level	
	Disaggregation	**Time frame**	**Disaggregation**	**Time frame**
Emitting sector	Agriculture Industrial processes Waste management Business Public	1990–2040	Ind' & Com' (other fuels)	2005–2018
	Energy supply		Ind' & Com' (electricity) Domestic (electricity)	
	Residential		Domestic (other fuels)	
	Transport		Transport	
	LULUCF		LULUCF	

We then explored city region-level mitigation scenarios for emissions across the domestic, commercial and transport sectors. For each sector, we:

- Identified a range of applicable low carbon measures.
- Assessed their per-unit investment costs and energy savings.
- Estimated their city-wide deployment potentials.

6.2 Transport sector

Analysis focused on the intra-city transport most prevalent in towns and cities across the UK:

- Cars and taxis.
- Heavy and light commercial vehicles.
- Buses and coaches.

The transport model was designed to estimate the costs, benefits and abatement potential of measures that would change current travel patterns. Estimating total emissions in the transport sector involved compiling emissions intensities for each mode of transport (CO2e/pkm) and city region-level mode share (pkms*) (see Figure 3).

First, we built a baseline based on existing travel patterns. Next, to build a scenario we induced changes to the transport system:

- Substitution of trips for different trips (Shift).
- Efficiency gains due to electrification (Improve).
- Reduced number of trips due to network/logistical efficiencies (Avoid; only use for freight).

Comparing the changes in distance travelled and energy used from the baseline, based on what influenced the change, we attributed costs and benefits to each low carbon measure such as shifting journeys from small petrol cars to walking, or the electrification of public buses.

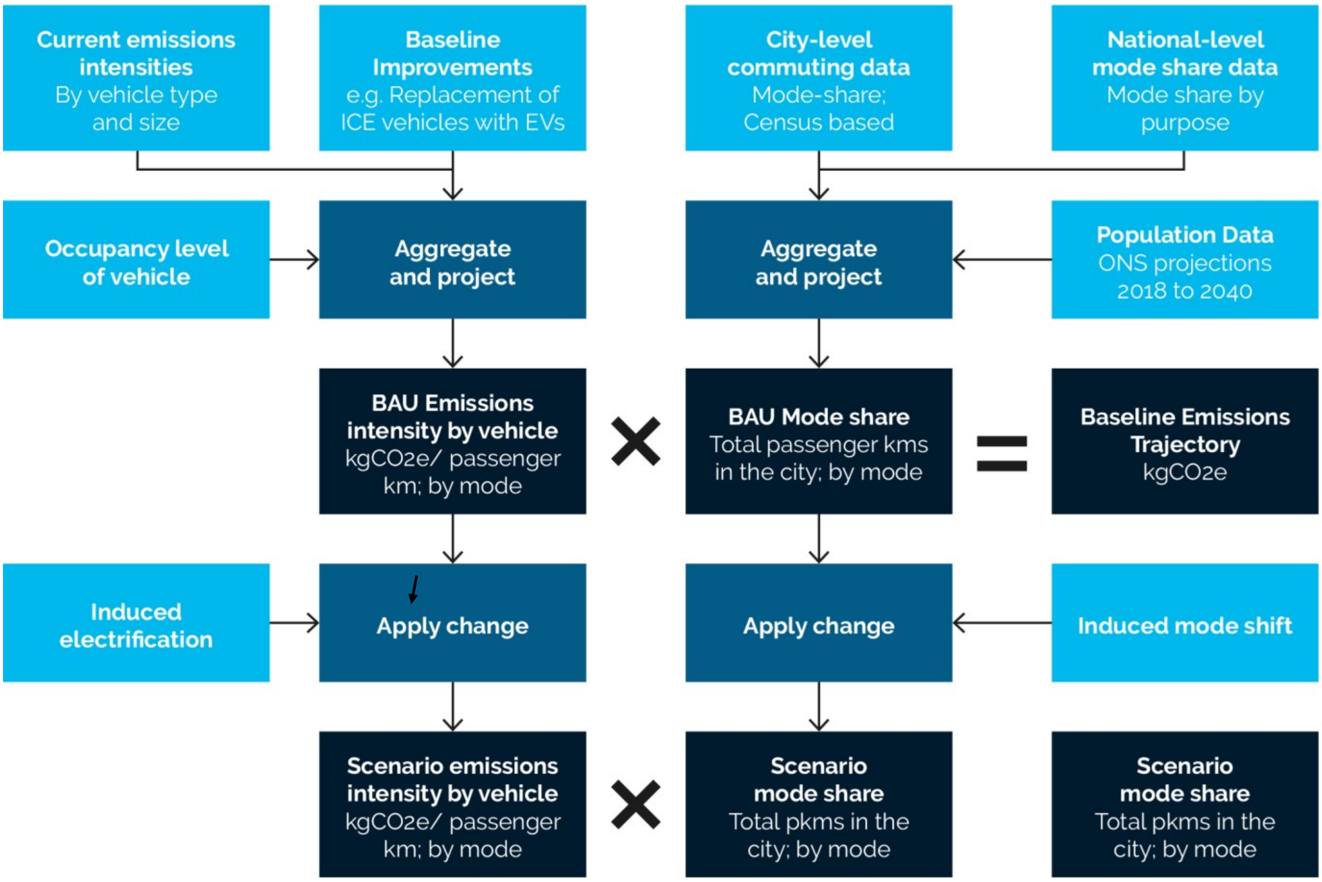

Figure 6-3: Flowchart outlining the transport sector methodology

In this study, rail, metro and tram travel were not considered. These make up 2% of journeys in most UK cities, (but 15% in London, which we did not model). We also excluded any changes to urban form because of the deployment of low carbon measures (e.g. decreased journey times leading to changes in trip lengths).

6.2.1. Low carbon measures

Table 6-2: Low carbon measures in transport sector

Category of low carbon measure	Description
Avoid	Improving the efficiency of the transport system, including integrated land-use planning and transport to reduce trip length.
More efficient logistics	Improving efficiency of the logistics system by better route planning or combining trips for multiple purposes.
Shift	Moving from the most energy consuming urban transport modes towards more environmentally friendly modes.
Car trips to walking	Walking generates no emissions, so shifting reduces carbon emissions from trips otherwise taken by car.
Car trips to cycling	Cycling generates no emissions, so shifting reduces carbon emissions from trips otherwise taken by car.
Car trips to buses	Buses generate emissions, but lower energy consumption and higher occupancy mean emissions per passenger-km are lower than for cars.
Improve	Enhancing the energy efficiency of transport modes, taking advantage of alternative energy use.
Electrification of private petrol and diesel vehicles	Petrol and diesel vehicles generate emissions on every journey, and electrification provides an opportunity for the energy used to be generated via renewable sources.

Electrification of distribution vehicles (HGV, OGV1 and OGV2)	Electrifying vehicles typically run on petrol or diesel provides an opportunity for the energy used to be generated via renewable sources.
Electrification of buses and coaches	Electrifying buses and coaches previously run on petrol or diesel provides an opportunity for some the energy used to be generated via renewable sources.

6.2.1 Financial costs and benefits

Costs and benefits were attributed to each low carbon mitigation measure by comparing the difference between the scenario and the baseline model runs to allow for system interactions. This difference in energy usage and/or distance travelled was used to attribute costs and benefits (calculated as net difference). Table 3 lists the costs and benefits included in our analysis. All costs are discounted at a rate of 3.5% except for those related to logistics: because they represent a cost directly to the private sector; a discount rate of 7% is used for logistics-related costs.

Table 6-3: Financial costs and benefits in transport sector

Cost or benefit	Title	Description
Cost	Discounted capital cost—charging infrastructure	The cost of chargers is worked out based on the number of extra EV kilometres driven in each scenario.

Cost or benefit	Title	Description
	Discounted capital cost—vehicle purchase	The net cost of electric vehicles over ICE vehicles, extra buses required, and bike purchases.
	Discounted capital cost—infrastructure	The cost of extra bike lanes and bus lanes required, based on a proportion of the extra bus riders and cyclists added.
	Discounted non-fuel operating costs (buses)	The extra operating costs associated with running buses—chiefly drivers' salaries. This metric is a cost in most city region/scenarios since more bus journeys are required.
Benefit	Discounted non-fuel operating costs (all vehicles)	Maintenance, oil, and tyres for all vehicles. This metric is a benefit in most city regions/scenarios since higher maintenance of buses is offset by much lower maintenance costs for cars, both because there are fewer cars and because EVs are cheaper to maintain.
	Discounted energy savings	The net cost of energy required to power the new journey patterns. This metric is a benefit in all city region/scenarios as electricity is cheaper than petrol/diesel, and walking/cycling is free.

To estimate a city region's residents' travel activity, we used a combination of city- and region-level data. Trips per person by mode and region were derived from the National Travel Survey (2017–2019) and average miles by mode from the 2011 census. Trips were adjusted for the local region where city region level mode share data was available. Population data were derived from ONS projections.

Data from the Department of Transport 'Transport Analysis Guidance' were used for vehicle occupancy and proportion of work and non-work trips. Following the process outlined in the flowchart in Figure 3, these inputs provided pkm by mode over the period 2021–2050.

The GHG emission intensity and cost of different travel modes were estimated using national datasets. The proportion of cars by fuel source and fuel and non-fuel operating costs by vehicle type were drawn from the Department of Transport 'Transport Analysis Guidance'. Energy prices were drawn from BEIS 2020 Updated Energy and Emissions Projections, and vehicle emission factors were derived from the UK Government Emissions Factors for Company Reporting, excluding electricity grid emissions factor projections, which were derived from BEIS 2018 Updated Energy & Emissions Projections.

A notable assumption was that we assumed that it is possible to shift as much as ~40% of car trips onto buses or bikes under the current system. This figure of 40% came from maximizing the total average distance walked and cycled per capita at 5.2km, based on the assumptions detailed below. The assumptions used to estimate a city region's residents' travel activity are provided in Table 4.

Table 6-4: Key assumptions in transport model

Metrics/Assumptions	Description	Source
Trips per year per person	Average number of trips taken per person per year by mode for that region.	Department for Transport Statistics - National Travel Survey - England: 2018/2019 (2 survey years combined).

Metrics/Assumptions	Description	Source
Distance travelled by mode annually	Average distance in miles travelled by mode annually across that region.	Department for Transport Statistics - Average miles travelled by mode, region and Rural-Urban Classification: England - All areas.
Total Oil Equivalent (TOE)	Total oil equivalent by transport mode was used to develop a baseline for motorised transport energy use in each local authority.	Total final energy consumption at regional and local authority level: 2005 to 2018. BEIS.
Maximum distance km cycling per person per day	2.7 km per person per day was assumed to be an upper limit for achievable cycling distance, based on levels achieved in Denmark.	https://www.regionh.dk/english/traffic/cycling/Documents/17751Cykelregnskab_UK.pdf
Maximum distance km walking per person per day	2.5 km per person per day assumed to be an upper limit for walking distance most shift, based on a literature review.	https://www.nhsinform.scot/healthy-living/keeping-active/activities/walking
Distance per year per vehicle	Kilometres per vehicle (and by vehicle type) per year was held constant across cities and across time. If a scenario shifted trips to motorised transport, then the number of new vehicles was determined using the number of additional kilometres by that vehicle type divided by the average annual kilometres by that vehicle type.	Transport Statistics for Great Britain. Department for Transport
Fast chargers per BEV	One fast charger for 80 battery electric vehicles and one for every 5 goods and/or transit vehicles.	Nicholas, M. and Hall, D., 2018. Lessons learned on early electric vehicle fast-charging deployments. International Council on Clean Transportation, Washington.
% trips by mode (2018 post only)	Total final energy consumption at regional and local authority level: 2005–2018 (BEIS) was used to determine travel by motorised vehicles. To estimate travel by non-motorised modes, NTS0103 was used to estimate the number of per person trips by bicycle and on foot. These values are regional and available only for English regions; as a consequence assumptions were made for cities in Wales, Scotland and Northern Ireland.	NTS0103: Average number of trips by main modes - index: England.
Average trip distance	Average trip distances are assumed to be the same across cities.	NTS0105: Average distance travelled by main modes - index: England.
Changes to urban form	We have assumed that the urban form of a city-region stays static, meaning that average trip lengths by mode remains constant. This assumption means that any major infrastructure projects that could drastically change the way we travel were not accounted for.	
Occupancy	Car and vehicle occupancies through 2036. Values held constant from 2036 through 2050.	TAG Table A 1.3.3
Occupancy—buses	Alteration from TAG source. Increased occupancy of buses from 14 to 17. This assumption was based on research undertaken by University of Leeds.	Source: Williamson, R. F., Sudmant, A., Gouldson, A., & Brogan, J. (2020). A Net Zero Carbon Roadmap for Edinburgh. Place-Based Climate Action Network: London, UK, 1-30.

Metrics/Assumptions	Description	Source
Proportion of car, LGV & other vehicle kilometres using petrol, diesel or electricity	The proportions drawn from this dataset were assumed to hold for all cities.	TAG Table A 1.3.9 Special consideration for Petrol/Diesel (set at 1%).
Vehicle energy use	Vehicle efficiencies were assumed to be the same across cities.	TAG Table A 1.3.11
Vehicle efficiencies	Data from the TAG is used in conjunction with academic literature to provide values for different vehicle sizes.	TAG Data Table A 1.3.11 And Chkaiban, R., Hajj, E.Y., Bailey, G., Sime, M., Xu, H. and Sebaaly, P.E., 2020. Fuel and non-fuel vehicle operating costs comparison of select vehicle types and fuel sources: A parametric study. In Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (pp. 284-293). CRC Press.
Share of kilometres by vehicle size	This dataset includes subset data to split heavy goods vehicles into types and passenger vehicles into large, medium and small.	VEH0124: Licensed vehicles by make and model and year of first registration: United Kingdom.
GHG emission factors	Scope 1 emissions factors were drawn from BEIS conversion factors. For Scope 2 emissions the reference scenarios for electricity production and generation sources were used to generate a baseline and annual conversion factors.	Conversion factors 2021: full set (for advanced users). BEIS. Appendix J: Total electricity generation by source Appendix G: Major power producers' generation by source.
Measures that are large in scale and diverse in scope	Shared electric vehicles — Assumed that 10 EVs are replaced by an EV that is part of a shared scheme. This assumption is a modifier used in the integrated scenario, modifying costs only. Shared bike scheme — Shared bikes were assumed to be used at ten times the rate at which private bicycles were used. Therefore, the cost of a shared bike was 0.77 times the cost of a regular bike. This assumption is a modifier used in the integrated scenario. Modifying costs only.	https://www.transportenvironment.org/sites/te/files/publications/Does-sharing-cars- really-reduce-car-use- June%202017.pdf https://inclusivev.eu/wp-content/uploads/2018/03/Inc EV-Executive-Summary.pdf
Marginal capital cost per vehicle	The marginal cost of electric vehicle relative to ICE equivalent e.g. electric car to ICE car.	TAG Table A1.3.14
Cost per fast charger	Faster chargers were assumed to cost £75,000, based on literature and consultation. This cost was the same for all vehicle types.	Mathieu, L. "Roll-out of public EV charging infrastructure in the EU." Transport & Environment 7 (2018).
Cost per bicycle	£505—Accounting for both the average cost of a bike alongside new entrant hard accessories.	http://eprints.lse.ac.uk/38063/1/BritishCyclingEconomy.pdf

Non-Fuel Resource Vehicle Operating Costs (NFOC)	The elements making up non-fuel vehicle operating costs include oil, tyres, maintenance, depreciation and vehicle capital saving (only for vehicles in working time). Following discussion with DfT, it was noted that NFOC contains a large depreciation component. DfT guidance can be found in the link below and the original document (1988) from which NFOC is derived is "Review of Operating Costs in COBA, EEA division of transport, 1990-91". This source shows that NFOC parameter a is made up of 36% oil, tyres and maintenance and 64% depreciation and that parameter b is 100% depreciation. Depreciation is a way of expressing capital costs on an annualised basis. Because our methodology is net, we only considered the additional capital costs of low carbon measures - e.g. an EV is X more expensive than an ICE car. This surplus is included in our capex calculations as an upfront cost and constitutes the only relevant capex for vehicles. Therefore, there should be no depreciation contained in any of our calculations. Therefore, for our calculations we used parameter a * 0.36 and did not use parameter b.	Table A 1.3.14: Non-Fuel Resource Vehicle Operating Costs https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.375.1581&rep=rep1&type=pdf
NFOC of electric vehicles	E-PSV, e-OGV1, and e-OGV were assumed to have half the operating costs of their ICE equivalents. Data from academic literature were used to provide values for different vehicle sizes.	TAG Table A 1.3.14 And Chkaiban, R., Hajj, E.Y., Bailey, G., Sime, M., Xu, H. and Sebaaly, P.E., 2020. Fuel and non-fuel vehicle operating costs comparison of select vehicle types and fuel sources: A parametric study. In Pavement, Roadway, and Bridge Life Cycle Assessment 2020 (pp. 284-293). CRC Press.
NFOC for cars—share of cars	It was assumed that all private vehicles have a utilisation for work at 18.2%.	Table NTS0409 from DfT (2019 table)
Additional NFOC for buses	Further NFOC to account for additional costs based upon the CPT index. It was assumed that for every £1 spent on fuel, £4.88 is spent on DRIVERS' wages, other labour and staff costs and insurance claims.	https://www.cpt-uk.org/media/ca2iuq21/chang e-in-bus-coach-industry- costs-for-the-12-months-to- 31-december-2019.pdf
Reference energy prices	Retail prices were assumed for all vehicles.	BEIS 2018 Updated Energy & Emissions Projections (Retail prices table)
Cost of buses lanes per km	Assumed cost of additional bus lane capacity at £250,000 per km.	Greener Journeys/KPMG (2017)

Metrics/Assumptions	Description	Source
Capacity of a bus lane	A reasonable planning-level capacity for a dedicated transit lane is 80 buses per hour.	https://nacto.org/publication/ transit-street-design-guide/introduction/why/desig ning-move-people/#:~:text=A%20reasonable%20planning%2Dlevel%20capacity,through%20a%20single%20transit%20lane.
Cost of cycling interventions	Assumption of £0.98m per additional km of additional cycling infrastructure, based upon a mixture of schemes such as cycle superhighway, mixed strategic cycle routes and resurfaced cycle routes.	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/742451/typical- costings-for-ambitious- cycling-schemes.pdf
Additional capacity of cycling infrastructure	Assumption that major shifts to cycling will require additional dedicated infrastructure to (a) handle additional bikes on the road (b) generate the interest and necessary shifts. Given the high capacity of cycling infrastructure, as well as the option for cyclists to use roads and alternative infrastructure, there is a high degree of elasticity between the shift to cycling and additional infrastructure required.	https://www.sciencedirect.com/science/article/pii/S2352146516305403?ref=pdf_download&fr=RR-2&rr=863c4871aba34057

6.3 Buildings sector

The purpose of these models is to estimate the financial costs, benefits and abatement potential of applying a variety of low carbon mitigation measures across 13 building archetypes in city regions across the UK. The building's models have been separated into domestic and commercial sectors.

The methodologies for estimating annual carbon savings in the domestic and commercial sectors are outlined in Figures 4 and 5. Annual carbon savings per-unit of each mitigation measure are multiplied by the number of units deployed in the mitigation scenario (per house in the domestic sector or per m^2 of floor-space in the commercial sector).

Per-unit carbon savings were obtained from the energy savings data we describe below and the associated emissions intensities. We also accounted for the interactions that occur when multiple low carbon measures are deployed within the same building, which can reduce the savings achieved in the case of, for example, solar photovoltaics and efficient lighting.

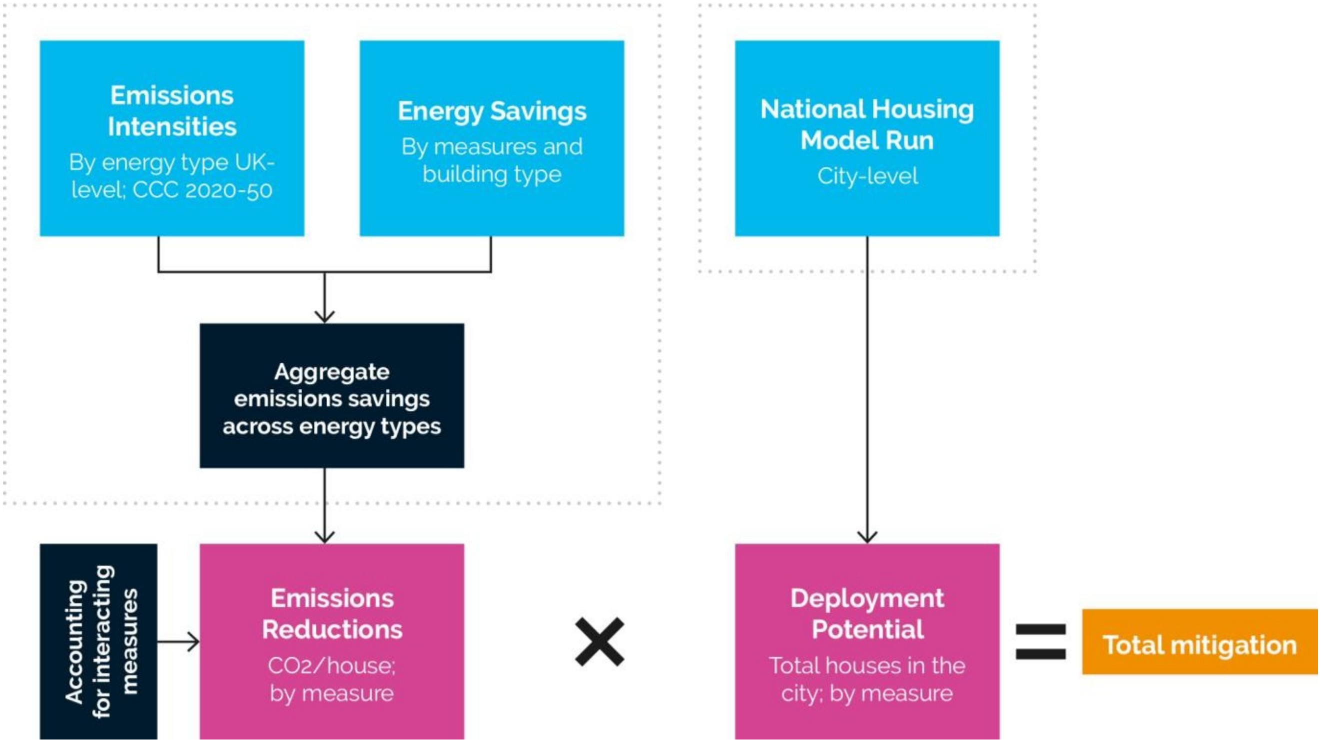

Figure 6-4: Domestic sector

6.3.1 Domestic building low carbon measures

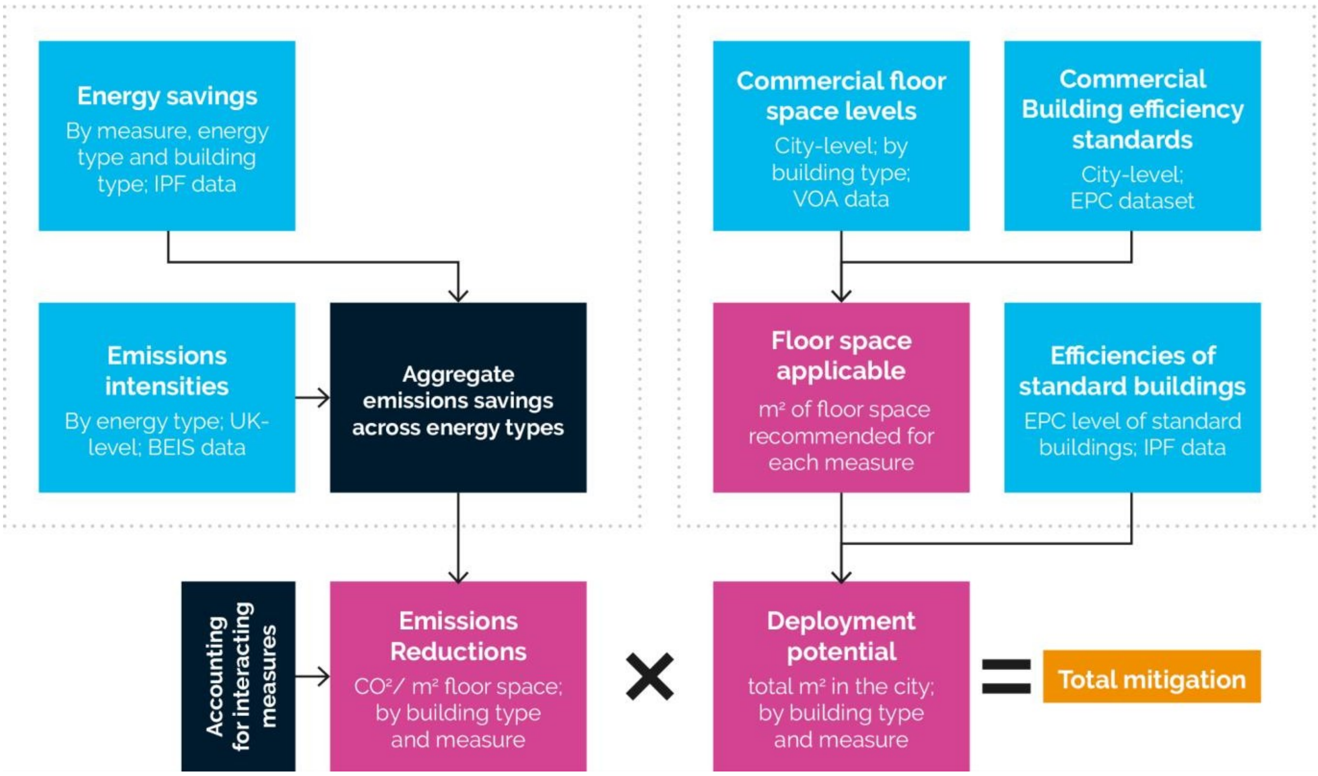

Figure 6-5: Commercial sector

In the domestic buildings sector, low carbon mitigation measures were deployed on a per home basis across the below archetypes:

- Bungalows.
- Converted built flats.
- Houses (detached, semi-detached, end of terrace, mid-terrace).

- Purpose built flats (high rise and low rise).

Table 6-5: Categories of low carbon measures applied to domestic buildings

Category of low carbon measure	Description
Energy efficiency	Upgrading gas ovens and appliances to energy efficient alternatives, gas hobs and ovens to induction alternatives, analogue to digital TVs, filament light bulbs to low energy lighting.
Insulation	Increasing air tightness, replacing single with double glazing, external shading, improving insulation.
Heating efficiency	Upgrading boilers to 95% efficiency, using heating controls, heat recovery, increasing efficiency of technology (e.g. DC drive fan coils, chilled beams).
Low carbon heat	Installing solar thermal or replacing gas boilers with air source heat pumps.
Microgeneration	Solar PV, installing a wind turbine.
Scale and scope domestic measures	Area-based commercial PV installation, area-based commercial retrofit scheme.

6.3.2 Public and commercial building low carbon measures

In the domestic buildings sector, low carbon measures were deployed on a floor area basis across six archetypes:

- Offices.
- Retail space.
- Industrial/warehouse units.
- Community centres.
- Education.
- Healthcare spaces.
- Hotels.

Table 6-6: Categories of low carbon measures applied to domestic buildings

Category of low carbon measure	Description
Energy efficiency	Increasing energy efficiency of light bulbs, daylight and movement sensors, increasing efficiency of technology (e.g. variable speed pumps,

	chillers).
Insulation	Installing insulation (cavity wall, external wall, floor, internal wall, loft), draught-proofing, top up loft, triple glazing).
Heating efficiency	Upgrading storage tanks and conventional boilers to gas combi-boilers, tank insulation, thermostats, radiator valves.
Low carbon heat	Replacing storage tanks and conventional boilers with heat pumps, use of solar thermal.
Behaviour change	Lowering thermostats, reducing heating for washing machines, reducing household heating by 10°C, reducing standby consumption, turning unnecessary lighting off.
Microgeneration	Solar PV.
Scale and scope commercial low carbon measures	Area-based commercial PV installation, area-based commercial retrofit scheme.

6.3.3 Financial costs and benefits

Table 6-7 lists the costs and benefits included in our analysis. Costs were discounted at a rate of 3.5%. However, if a cost is directly applicable to the private sector (e.g. measures applied to retail units) a discount rate of 7% was used.

Table 6-7: Calculated financial costs and benefits in buildings sector

Capital cost	The capital costs of low carbon measures were estimated in net present value terms over the period from 2022–2050 taking into account: - When the new low carbon measure was assumed to be deployed. - The expected length of life of the low carbon measure before it requires replacement. Note - The total net present investment cost was applied on deployment between 2022 and 2030. Therefore, the cost of replacement was not realistically spread across the study period.
Energy savings	The deployment of each measure between 2022 and 2050 was multiplied by the estimated energy savings (for electricity, gas and other) associated with each low carbon measure, multiplied by the discounted energy cost forecast from BEIS. As per BEIS Green Book guidance, we used long-run variable costs because energy prices include—Fixed costs that will not change in the long run with a small, sustained change in energy use; Carbon costs, since these are valued separately; and taxes, margins, and other components that reflect transfers between groups in society.

Unlike in the transport model (where it was assumed that the price of EVs is likely to fall to reach parity with ICE cars by 2035), the cost of all buildings-related measures in this study stayed the same in real terms. The basis of this assumption is that most buildings measures, such as insulation and boilers, are very mature technologies and less likely to be subject to significant innovation.

6.3.3.1 Domestic sector

For the domestic sector the list of low carbon measures, their lifetimes, and their costs and energy savings (electricity, gas, and other fuels) are consistent with the UK's National Housing Model (NHM), which was developed by the Centre for Sustainable Energy (CSE). It is worth noting that these costs have been tested and updated each time the models have been used by local authorities, most recently in 2020.

The (Energy Performance Certificate) EPC data sets represent the full housing stock by local authority, including information on current insulation levels, heating systems, etc. on a per property basis. Using EPC datasets in conjunction with these NHM outputs, we assessed what low carbon mitigation measures were appropriate for a particular city's domestic sector and for how many houses each measure would be suitable. This output is referred to as the deployment potential.

Using a s-curve deployment profile, each mitigation measure was deployed to its potential within the constraints set by the scenario. Therefore, we could calculate what energy and emissions savings would be expected, assuming the household maintains the same heating regime post-installation of each measure. The rebound effect has been accounted for; see Table 8. Also, the buildings stock was taken as static—i.e. we did not increase homes each year commensurately with likely house growth.

6.3.3.2 Public and commercial

In our model, the Public & Commercial buildings sector operates in largely the same manner as the domestic sector, although we changed the basic unit of analysis from individual homes to m^2 area of applicable non-domestic floorspace. For the commercial sector we obtained lists of low carbon mitigation measures and their lifetimes, costs, and energy savings (electricity and gas) from the review of the Investment Property Forum (IPF), which are appropriate throughout the UK. Mitigation measures were then assigned to different building types, with (marginal) costs and (multi-vectoral) energy savings detailed on a measure-by-measure basis.

To calculate city region level deployment potentials, we utilised data at the Local Authority (LA) level describing:

- Existing commercial floor-space by building type from the Valuation Office Agency (VOA).
- Energy Performance Certificate (EPC) assessments reported for commercial building stock across LAs.

We used these datasets together to estimate the floor-space in a city region across each archetype. We assumed that the area of commercial floor space remains static across each of these archetypes. This assumption appears reasonable as for the periods within which data were available there were only negligible changes in the distributions of EPCs of commercial buildings and existing commercial floor space. We used the proportion of floor space surveyed in EPC assessments that recommended a particular intervention and applied this to the total floorspace in a city region

Table 6-8: Key assumptions in the buildings model

Metrics/Assumptions	Description	Source
Heat pump costs	Conducted brief review of the Centre for Sustainable Energy (CSE) measures and inflated all to 2020 prices. All looked reasonable except for heat pumps—the deployment of this technology is potentially central to the transition and likely to be in high demand and, subsequently, high supply. We found accurate up-to-date costs from the UK Government (see link) and used these to update the cost of heat pumps.	https://www.gov.uk/gover n ment/publications/cost-of- installing-heating-measures- in-domestic-properties
Heat pump cost reduction	Heat pump cost reduction has been applied in all scenarios in line with the Net Zero Strategy (NZS): The NZS stated that there is an ambition by the UK government to reduce the cost of heat pumps by at least 25% to 50% by 2025 and to reach price parity with gas boilers by 2030. Therefore, the price of an average heat pump used in the analysis would fall each year until 2030, when it would reach the same real price as an average gas boiler.	https://www.gov.uk/gover n ment/publications/net-zero- strategy
Heat pump deployment	Heat pump proportionality was assigned per population in each city region (based on the Government policy objective of 600,000 heat pumps provided each year from 2028 onwards), with deployment starting in 2022 and exponentially increasing to 2028, when 600,000 heat pumps would be deployed each year. The proportion of the original heat pump deployment across property types was calculated to split the updated deployment figure across property types.	
District Heat Network deployment	District heating networks currently supply 3% of the UK's heat supply: the aim is to increase the share to 20% by 2050. The Net Zero Strategy assumes that 6% of heating supply will be provided by district heating networks by 2035.	

	To develop a deployment potential for district heat networks in the place agnostic scenario (ie not place-specific), proportionality was assigned per population in each city region in the same manner as heat pump deployment. Note: this deployment process means that heat networks were assigned to cities based on population but not based on the factors that will actually drive heat network deployment at the very local level: density, local heat sources and other local project feasibility factors.	
Deployment potential figures	The deployment potential for each low carbon mitigation measure for each property type was calculated for each city region based on EPC data; data was gathered on whether the low carbon measure could be deployed within a household and then aggregated up to the relevant low carbon measure group.	https://epc.opendatacomm u nities.org/
S-curve deployment of buildings mitigation measures	In all scenarios, it was assumed that deployment of building mitigation measures would start slowly in 2022 and build to a peak in the late 2020s before tapering off. An S-curve was applied here rather than a linear growth rate.	

Metrics /Assumptions	Description	Source
Interactions methodology	We assumed that mitigation measures that impact the heating of a home will interact. Given that a household will use a certain amount of energy for heating, each low carbon measure will reduce the savings available for other measures. The following equations were applied to account for this adjustment: Corrected energy/carbon savings = original savings - original savings * (average house % savings w/o interactions - average house savings w/ interactions) Average house % savings w/o interactions = average number of interacting low carbon measures per house * average % savings per measure Average house savings w/ interactions = average savings per measure ^ number of low carbon measures Although cooling measures would also interact, the deployment is significantly lower for cooling low-carbon measures than heating measures, and so the impact would be negligible.	
Scale and scope of low carbon mitigation measures	- District heating networks—The cost and benefits were based on figures from a case study in Tallaght. - Whole house retrofit—measures that would be replaced by a whole house retrofit were summed and compared with desk research values. It was found that this output represented ~31% saving. This reduction was applied to other property types. The electricity, gas and other savings were reduced by approximately 10% overall. - Low energy apartment retrofit—the same method was used, and the same percentage reduction was applied. - Area-Based Commercial Retrofit Scheme—mean retrofit data comparing costs of typical schemes vs. individual low carbon measures for a range of commercial typologies (5) was used as a cost reduction on the sum cost of low carbon measures. - Area-Based Commercial PV Installation—the average values of the three existing low carbon measures was used, and a costing improvement from economies of scale data was used as a proxy for an area-based approach.	https://carbonneutralcities.org/wp-content/uploads/2018/05/1-London-Energiesprong-Transferability- Assessment.pdf , https://www.aecb.net/wp-content/uploads/2015/08/Going-Deep.pdf, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/656866/BEIS_Update_of_Domestic_Cost_Assumptions_031017.pdf , https://www.codema.ie/images/uploads/docs/TDHS_Marketing_Brochure_for_Developers.pdf https://www.hw.ac.uk/uk/schools/doc/egis/TARBASE_ND_REPORT.pdf , https://www.london.gov.uk/sites/default/files/appendix_a_solar_action_plan.pdf , https://www.theguardian.com/environment/2016/may/19/london-borough-installs-6000-solar-panels-on- market

Metrics /Assumptions	Description	Source
Rebound effect	For some domestic low-carbon measures (LCMs), an increase in energy efficiency would lead to increased use of energy to provide more comfort. We assumed a rate of 15% rebound for certain measures and valued this rate using BEIS guidance —see 'Home Comfort' on p. 25.	Committee for Climate Change (2013) —discussion of how the energy savings potential of low carbon measures (LCMs) is rarely reached because of in-use, comfort and inaccessibility factors. This analysis only considered comfort factors, but the context may be useful for further analysis. UK Energy Research Council (2007) —offering extensive evidence of the size of the rebound effect in different settings and concluding that "The direct rebound effects were estimated to reduce overall energy savings by 15%."

6.4 Social costs and benefits

Besides their financial costs and benefits, each low carbon measures (LCMs) would create various wider social costs and benefits. These costs and benefits were identified and defined using impact pathways, drawing on the extensive existing literature that has considered the potential impacts of urban decarbonisation. Taken together, the financial costs and benefits plus the wider social costs and benefits provided our estimates of the net present social value (NPSV) of each low carbon measure.

Figure 6 summarises the key impact pathways identified in relation to the low carbon measures relevant to surface transport, and Figure 7 does the same for heat and buildings.

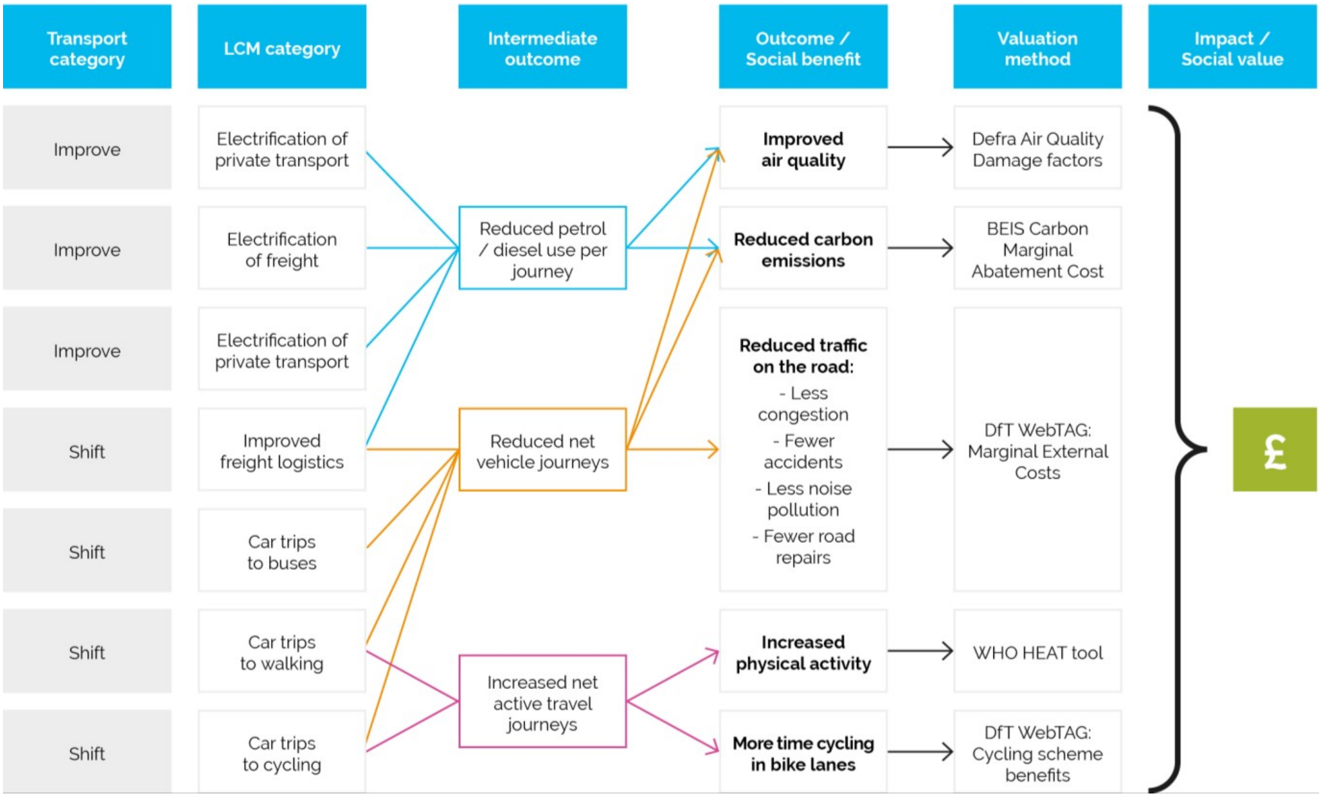

Figure 6-6: Simplified impact pathway for surface transport low carbon measures, by category

All social benefits are presented as positive benefits ('Improved air quality'). In aggregate, net benefits are generated under all scenarios, but they include both costs and benefits. For example, switching car trips to buses results in a benefit of fewer cars on the road, leading to reduced carbon emissions, congestion, accidents. However, the impact of more buses on the road results in increased carbon emissions, congestion, accidents.

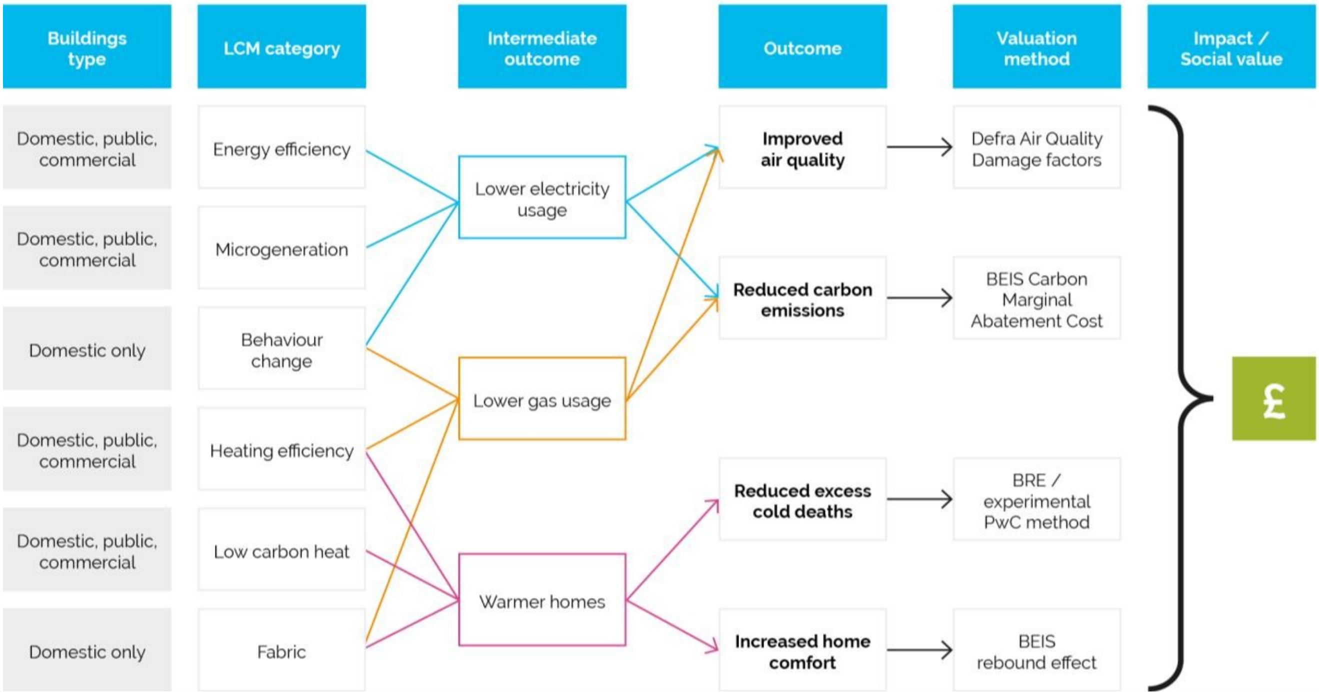

Figure 6-7: Simplified impact pathway for buildings low carbon measures by buildings type and category

Scale and scope low carbon measures are not shown; not all individual pathways shown e.g. some heating efficiency low carbon measures also would reduce electricity usage, but they would reduce gas usage far more as most UK homes have gas boilers.

6.4.1 GHG emissions

As per BEIS guidance: "Greenhouse gas emissions values ("carbon values") are used across government for valuing impacts on GHG emissions resulting from policy interventions. Carbon values represent a monetary value that society places on carbon dioxide equivalents (£/tCO2e). They differ from carbon prices, which represent the observed price of carbon in a relevant market (such as the UK Emissions Trading Scheme). The government uses these values to estimate a monetary value of the greenhouse gas impact of policy proposals during policy design, and after delivery." BEIS Valuation of greenhouse gas emissions: for policy appraisal and evaluation, updated Sep 2021, Annex 1, is the key source for this analysis.

- Step 1: The annual net GHG emissions savings from the transport and buildings models.
- Step 2: These emissions savings are multiplied by the carbon price for the appropriate year.
- Step 3: The estimated benefits are discounted at 3.5% to derive their net present value.

By considering the change in use of different types of energy because of low carbon measures, it is possible to split the carbon values into traded and non-traded values. For example, as per BEIS guidance, electricity forms part of the traded sector, but domestic gas use is in the non-traded sector.

We do not present this analysis in our main findings or supplementary evidence, because the updated guidance and further correspondence with the BEIS GHG appraisal team suggests that (1) the usefulness of this disaggregation in a broad, hypothetical appraisal such as this study is limited, and (2) the methodology is subject to change pending consultation on design of the UK ETS.

6.4.2 De-congestion benefits

Our assessment of the potential benefits of reduced congestion followed the approach recommended in the Department for Transport's WebTAG relating to Marginal External Costs, which builds on an academic paper from Samson et al (2001)[4].

MECs measure the change in social value in having one less car on the road because of different factors, as follows:

1. Less congestion results in improved journey time and quality and lower vehicle operating costs.
2. Fewer accidents results in lower mortality and morbidity.
3. Fewer road repairs required equates to lower cost to the Exchequer.
4. Lower levels of noise pollution result in lower health and productivity burden.
5. Fewer GHG emissions.
6. Lower air pollution.
7. Lower road/fuel duty to the Exchequer.

Note that 5 and 6 are valued elsewhere in our analysis (so not used here), and 7 is a transfer from one group to another.

We used two sheets from the Tag MEC data—A5.4.1 (traffic data) and A5.4.2 (cost data) for valuation.

The output from the transport models was vkms for different vehicle types, per year, but these outputs were not split by region or road type. Therefore, the first step required was to:

Step 1: Split total vkms in each city region into different region and road types.

This disaggregation was done using UK Government's DfT WebTAG Sheet 5.4.1: "Traffic by region, congestion band, area type & road type."

- Assumption: Regions are at the International Territorial (NUTS-1, i.e. Scotland, North-East, London); it was assumed that each city region has the same transport road usage as the region in which it is located. So, for example, Manchester and Liverpool both use North-West.
- Assumption: There is no regional split for Northern Ireland, so Wales was used instead as Swansea-Bay and Belfast city regions have similar levels of density.
- Assumption: DfT's regional road-usage splits (5.4.1) change every 5 years but stays constant between them.

This methodological approach allowed us to say that, for example, if 100km is driven by a car in Glasgow city region, then X% of it will be on an A road in an Inner conurbation. So, if 100km less is driven, then it will disappear from this same road/region.

DfT gives values in pence per vehicle kilometre (vkm) avoided, split by the mode, place and time the vkm is avoided, by:

- Vehicle type (Cars, LGVs, OGV, HGV and PSV).
- Year (2015–2050).
- Region (London, Inner and Outer Conurbations, Other Urban, Rural).
- Road type (Motorways, A roads, Other Roads).
- Congestion band (1 to 5; describes what % of the time each road is expected to be in free-flowing traffic (band 1) or standstill (band 5)).

1 and 2 are outputs from the transport model, and 3, 4 and 5 are calculated using web tag A5.4.1 above.

Step 1. From above section.

Step 2. Multiply the avoided vkms per mode, place and time by the pence/vkm value for the corresponding mode, place and time.
Step 3. These benefits are discounted at 3.5%.

[4] Sansom T, Nash CA, Mackie PJ, Shires J, Watkiss P (2001) Surface Transport Costs and Charges: Final Report. For the Department of the Environment, Transport and the Regions. Institute for Transport Studies, University of Leeds

6.4.3 Air Quality

We assessed the value of the impacts on air quality using the damage cost guidance prepared by the Department for Environment, Food and Rural Affairs (Defra). The Defra approach considers different health impacts based on the latest advice from Public Health England and the Committee on the Medical Effects of Air Pollution (COMEAP). Three impact pathways were included in this valuation:

- public health.
- the natural environment.
- the economy.

Detailed information on derivation of this methodology is available here.

There are two Defra tables—one for air quality damage from transport emissions and one for fuel combustion from buildings. Both assume that damage is higher when fuel is consumed in more densely populated areas. They also require the user to calculate where each unit of fuel is used. However, the two tables use different "density areas", as shown.

Table 6-9: Density areas used to assess air quality damage in buildings and transport

Buildings
National Average
Domestic: Inner Conurbation
Domestic: Urban Big
Domestic: Urban Medium
Domestic: Urban Small
Domestic: Rural

Transport
Transport Average
Central London
Inner London
Outer London
Inner Conurbation
Outer Conurbation
Urban Big
Urban Large
Urban Medium
Urban Small
Transport Rural

Step 1: Split each local authority in each city region into a transport and buildings density-area type. This disaggregation was done using either (depending on data availability):

- For buildings—The density of the LA was matched to ONS population stats, with each building's density area being assigned to a different density quintile.
- For transport—Allocations from Table 6 of the National Transport model, and where these allocations were not present for a place, ONS density data was used (as per section above).

* Note that neither of these methods have any relation to the splitting of vkms into road types in the section 3.2.3.

Step 2. Multiply the damage factors per fuel type, per year, per density area by the change in energy usage by fuel type per low carbon measure per year. For transport, vehicle type split is also required.

Step 3: These benefits were discounted at 3.5%. In addition, there is no annual data series for transport air quality damage, so damage costs were inflated to 2022 prices and then 2% p.a. as per the Defra guidance.

- Assumption: Air quality (AQ) damage includes both health benefits and non-health benefits (i.e. changes to productivity); therefore, we used the discount rate of 3.5% and not the pure health benefits rate of 1.5%.

6.4.4 Physical activity

Our estimate of the health benefits associated with the change in levels of physical activity associated with adoption of different low carbon measures was based on the World Health Organisation's health economic assessment tool (HEAT). World Health Organisation - online Health Economic Assessment Tool (HEAT) for walking and cycling. The methodology was improved following correspondence with the authors, based on the academic paper that informs the methodology[5].

Assumption: The academic paper (Kahlmeier et al., 2011[6]) that underpins the methodology assumes that health benefits only accrue to people between ages 20 and 74 for walking and between ages 20 and 64 for cycling since there is no evidence otherwise. We assumed that all extra vkms travelled by active travel are completed by this age group. This assumption is reasonable since:

- loss of life due to lack of physical exercise is very unlikely before age 20.
- frequency of exercise drops for those over age 75, who are half as likely to walk regularly and for those over age 65, who are three times less likely to cycle regularly than the population aged between 20 and 64.
- In addition, the age groups from Kahlmeier et al. (2011) are broken down further because the younger group (20-44) has a much lower risk of mortality—see step 5.

Step 1: Our transport model estimates the extra vkms being walked and cycled per year.

Step 2: Divide by the age grouping populations, average walking/cycling speed (from HEAT; 14km/h) and 365 to give hours of exercise per person per year, assuming all people split the exercise evenly.

Step 3: Use HEAT calculation: Divide the extra exercise per person in each age group by the reference range given by HEAT, and then multiply by the total reduction in risk that is associated with the reference range (see HEAT tool).

Step 4: If the volume of exercise exceeds the capped amount, then cap. Note – this threshold is not reached in any of the modelled scenarios as the cap is equivalent to 450 minutes per week of cycling or walking.

Step 5: Multiply the reduction in risk for each age group by the total all-cause mortality for each age group in a given city region. This output gives the total number of mortalities per city region per year that would be avoided by increased physical activity.

Step 6: Calculate the average number of life years remaining for each age group—e.g., older age groups are likely to live less long.

Step 7: Multiply this output by the number of expected mortalities (5) and the VOLY to give a total value of

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[5] Götschi, T et al (2020) Integrated Impact Assessment of Active Travel: Expanding the Scope of the Health Economic Assessment Tool (HEAT) for Walking and Cycling. Int. J. Environ. Res. Public Health

[6] Kahlmeier, S., Cavill, N., Dinsdale, H., Rutter, H., Gotschi, T., Foster, C., & Racioppi, F. (2011). *Health economic assessment tools (HEAT) for walking and for cycling* [Monograph]. World Health Organization. https://researchonline.lshtm.ac.uk/id/eprint/2572594/

life lost per year.

Step 8: Create a lag so that it takes 5 years to accrue total benefits, with 20% created in the first year, 40% in the second, etc.

Step 9: Discount by 1.5%: We used the Green Book recommended discount rate for health benefits as they are pure health benefits.

6.4.5 Excess cold

Our estimates of the social costs and benefits associated with the avoidance of excess cold followed an experimental method based on evidence from Building Research Establishment (BRE) and Cambridgeshire County Council[7]. BRE estimated the potential NHS savings if 25 different housing hazards were eliminated in the UK. The largest hazard is "excess cold," which was estimated to cost the NHS £848m in 2015 (£1.4bn in 2020 prices). The approach set out below allocates a proportion of these potential savings to the successful deployment of low carbon measures that increase domestic warmth.

This approach is experimental, was designed for this study and should be used with caution as the causal pathway from improved housing measures to lowered likelihood of morbidity or mortality from excess cold is complex, and this study does not have sufficient data to draw a direct line from one to the other.

However, the assumptions used are conservative and the resulting benefits are not significant to the overall analysis (excess cold benefits represent ~1-5% of all social benefits in any given city region/scenario).

- Assumption: The model does not contain information on income distribution, so it is assumed that all low carbon measures generate the same level of benefits, even though insulation in a poorer household would be more likely to eliminate excess cold.
- Assumption: Excess cold creates wider social costs through lost productivity and reduced utility (it is unpleasant to live in a cold home). This study did not consider the former at all, which is likely to be significant, but the latter is included in "Home Comfort" benefits (see next section).
- Assumption: This method assumes a direct link between temperature increase and health benefits and makes no provision for other impacts of temperature e.g. (1) increased temperature may also decrease dampness, which has health benefits; (2) increased insulation may increase the likelihood of excess heat in summer, which has health disbenefits not considered in this study.
- Limitation – Despite their potential impact on reduced excess cold in UK homes in the future, increased temperatures resulting from climate change have not been modelled through to 2050 due to their unpredictability.

Step 1: Calculate the total value to the NHS of eliminating excess cold. Two datasets were combined:

- The BRE data showed that 60% of total NHS costs are due to excess cold (£848m of £1.4bn).
- The Cambridge Research Group data showed that the total cost to the NHS of all housing hazards is £2bn p.a.
- Therefore, we assumed that a cost to the NHS of £1.2bn p.a. can be associated with cold-related housing hazards that can be tackled by warming low carbon measures (60% x £2bn).
- This estimate is inflated to 2020 prices to give a figure of £1.43bn NHS costs.

Step 2: Allocate NHS costs to city regions. Total NHS costs were split between city regions on a population basis but weighted for that city's experience of excess winter deaths in 2018/19 (i.e. pre-COVID).

- Assumption: Weighting NHS costs per city region by observed excess winter deaths: Excess cold deaths depend on many factors, including ambient winter temperature, housing stock and poverty levels of a city. In the absence of an analysis of these factors, we assumed that observed excess winter deaths in a

[7] BRE (2015). Understanding the cost of Poor Housing to Health. Available from <https://www.gov.uk/government/publications/homes-and-ageing-in-england-understanding-the-cost-of-poor-housing-to-health>

city region could be considered indicative of them all.

- Assumption: Excess cold baseline: Analysis of long-term trends showed that excess winter deaths in the UK are falling by approx. 1% p.a. even as the population rises. This trend may be because of the factors mentioned above (warming temperature, improved housing), and it means that in the absence of low carbon measures, NHS costs would be reduced over time. Therefore, this long-term trend was extrapolated and used to reduce the total amount of NHS savings available by ~1% p.a.

Step3: Allocate NHS costs to each low carbon measure deployed.

Domestic low carbon measures that increase heat were selected (67 out of 235).

- Assumption: Only low carbon measures that increase temperature infer 'anti-excess cold' health benefits—therefore, insulation were included but heat pumps were excluded.

The temperature increase of each was used to calculate a warming factor per low carbon measure using data from National Housing Model / SAP scores—see Standard Assessment Procedure - BEIS 2013.

- Assumption: There is a direct, linear relationship between the extent to which a measure increases temperature and that measure's reduction in NHS costs.
- Assumption: Measures that lower heat—thermostats, behaviour change—were assumed to not be deployed by households that are already cold; therefore, there was no excess cold disbenefit applied to those measures.

The warming factor was corrected by deployment potential so that 70% of max deployment equals 100% of NHS cost savings.

- Assumption: An assumption had to be made about whether total excess cold is fully eliminated when all possible EPC measures are deployed or at a lower level. This analysis assumed a level of 70%. This assumption was based on evidence showing that 37% of all homes surveyed in England have at least one significant hazard[8], which means that the total NHS costs could be avoided if only those 37% of homes received warming low carbon measures. However, it is not possible to disaggregate at the household level so an assumption was made that once deployment reaches 70% of potential, all the at-risk 37% would be covered.

Note: A more means-tested rollout of warming low carbon measures would generate higher NHS savings faster, but a more market-based approach (incentives to install insulation that incentivise richer households first) would likely result in a slower reduction in excess cold.

Use the corrected warming factor to assign a total £ value for each low carbon measure in each city. The total NHS costs can now be split between low carbon measures so that, for example, in an average bungalow cavity wall insulation installed between 1976 and 1983 is worth £140 p.a. in avoided NHS costs.

Multiply these £ values by the number of each low carbon measure deployed in each city region/scenario each year.
Discount benefits at 1.5% (these benefits are pure health benefits so discounted at reduced rate).

6.4.6 Home comfort

This benefit follows BEIS guidance[9] on how to value the additional comfort that households receive from being able to use domestic appliances (e.g. heating, lighting) more when the energy efficiency of the appliances improves. This benefit values the "rebound effect". This effect is the extent to which energy efficiency measures result in households saving money on their energy bills, enabling them to afford to use these appliances more, leading to an improved quality of life (i.e. warmer, more well-lit homes).

[8] https://files.bregroup.com/bre-co-uk-file-library-copy/filelibrary/pdf/87741-Cost-of-Poor-Housing-Briefing-Paper-v3.pdf
[9] Valuation of energy use and greenhouse gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government (October 2021)

From the domestic buildings model: the deployment of those low carbon measures where a reduction in energy usage (and therefore energy bills) may lead to higher usage (148 measures out of 235). For example, a more efficient oven is included but lowering a thermostat is excluded. Heat pumps are also excluded as they are more likely to increase fuel bills, so there would be no rebound effect.

- Assumption: In practice, the extent to which the rebound effect is present differs significantly, but a central rate of 15% was chosen for all measures.
- Assumption: 0% rebound effect was applied for public and commercial usage: the BEIS guidance gives some evidence that offices, schools, hotels etc. are not constrained by energy prices to the same degree as households.
- Assumption: Indirect rebound effects are not considered at all—i.e. where money saved on energy is spent in the wider economy, increasing enjoyment.
- Assumption: Rebound rates remain at 15% throughout the study—there is no reduction over time thanks to exogenous changes to buildings standards or energy prices.

Step 1: Select domestic buildings low-carbon measures (LCMs) that are subject to a rebound effect.
Step 2: Select which type of energy usage the rebound would be applied to: For example, triple glazing results in gas savings (boiler usage) but not electricity savings, so the rebound effect applies only to gas; low-energy lighting only affects electricity use; a gas combi-boiler saves both electricity and gas.
Step 3: Calculate 15% of the energy savings for each measure each year in kWhs.
Step 4: Multiply per-unit energy savings by the number of measures deployed each year and by the retail price of that measure.

- Assumption: Analysis of costs in this study always used the long-run variable cost of energy, but the rebound effect used the retail price. This methodology follows BEIS guidance: because the retail price is the price households pay to increase their heating or lighting; it is therefore a revealed preference of their willingness to pay for this experience.

Step 5: Benefits were discounted at 3.5%.

6.4.7 Bike lane ambience

We followed Department for Transport guidance on the extra journey quality a cyclist receives when cycling in a bus lane, as opposed to an open road. When cycling in a bus lane cyclists feel safer and have less-interrupted journeys. Many cyclists would be willing to pay a small amount for this extra benefit, and DfT has created a methodology that seeks to capture that value created.
Note that the total value of this measure is small (<1% of all social benefits), and in our main report and economic supplementary analysis we did not present it separately but as a part of physical activity benefits—but the methodology used was distinct.

DfT WebTAG A4.1.6: Value of journey ambience benefit of cycle facilities.

Step 1: Translate bike vkms into minutes spent cycling each year by dividing by average cycling speed (14 km/h).

Step 2: Create a constant (17%) to understand how much of this time is spent in bike lanes by multiplying the assumed % of all kms spent in bike lanes by the assumed difference in speed in bike lanes versus the road.

- Assumption: 20% of all kms travelled are in bike lanes. There is very little data on what proportion of time cyclists spend in bike lanes versus the open road in UK cities, but 20% is thought to be a reasonable level for non-London cities. This is based on the lower availability of bike lanes compared to the road network in UK cities [10], but clear research on preferences for cyclists to use cycling facilities during their journey[11]. Due to gaps in the literature a more robust estimate was unable to be found.
- Assumption: Cyclists travel 15% faster in bike lanes because of fewer interruptions. There is very little data on difference in speeds in bike lanes, but this assumption is similar to the moderate scenario found in Rayaprolu et al. (2018)[12], resulting in greater speeds from fewer interruptions in bike lanes and

[10] https://www.colas.co.uk/how-cycle-friendly-are-uk-cities/
[11] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6351222/
[12] https://journals.sagepub.com/doi/epub/10.1177/2399808318797334

highways.

Step3: Multiply total bike minutes p.a. by this constant to give bike lane minutes p.a. for each city region/scenario.

Step 4: Calculate the average benefit generated per minute of cycle lane usage by averaging the 5 types of bike lane given in WebTAG.

Assumption: This study assumed that a given level of bike usage would create demand for more cycle lanes but not what type of lanes. DfT provides values for time spent in (1) off- road segregated cycle track, (2) on-road segregated cycle lane, (3) on-road non- segregated cycle lane, (4) wider lane, and (5) shared bus lane. We assumed that journeys would be split evenly between all five, and so used the mean value of 3.79 pence per minute.

Step 5: Multiply bike lane minutes p.a. by this value to generate total benefits.

Step 6: Benefits were discounted at a rate of 3.5%