A computation-enabled analytical construct for the assessment of alternative urban conditions towards sustainable transport system and to support sustainable travel activities: a space time constraint-based approach

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A computation-enabled analytical construct for the assessment of alternative urban conditions towards sustainable transport system and to support sustainable travel activities: a space time constraint-based approach

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Abstract

The contribution of anthropological emissions to climate change has been a widely acknowledged topic of concern in recent decades towards environmental sustainability. Urban land-based transportation for the movement of people is one of the main contributors to emissions in the UK and other countries. Environmental sustainability is most directly achieved through the reduction of motorised transport activities, including passenger transport, but travel activities related to social and economic activities must be supported in cities.

Chapter 1 problematises the goal to support social and economic activities whilst reducing environmental impact as a challenge in planning and city design. The challenge within city design processes is identifying the implications of alternative urban conditions towards urban sustainability before they are built. There is a lack of an adequate computational analytical framework that considers new urban developments and new transport services in the analysis of alternative urban conditions.

Chapter 2 identifies known methodological approaches to analyse alternative urban conditions before the fact (ex-ante). Each supported by after the fact (ex-post) studies correspond to the theoretical perspective underlying each approach. A space-time approach has advantages over other probable outcome-based approaches in transport-integrated city design towards transport and travel-related sustainability. However, a space-time approach has been underdeveloped for before the fact (ex-ante) analysis. This study aims address this research gap by extend ingthe space-time approach as a computational analytical construct to facilitate computational scenario modelling and analysis for transport-integrated city design.

Chapter 3 outlines the theoretical framework of a space-time approach for architecture in city design. A space-time approach includes the opportunities for activity participation related to the spatial and temporal organisation of building functions and programme, physical spatial transport infrastructure, travel modes, space and time-sensitive public transport services. Together, they facilitate and constrains the inhabitants' possibilities to conduct different combinations of everyday activities.

Chapter 4 details the constructive research method employed in this study. This study results in the construction of a computational analytical construct in two parts. First, an operational model extends a space-time analytical approach by integrating new technologies and data sources, with the ability to manipulate the model reflecting alternative urban conditions. Second part consist of an analytical framework for travel mode comparison in alternative urban conditions to address questions in transport and travel-related sustainability within future built environments.

Chapter 5 describes the construct implementation and the interpretation of results. The operational model is tested using two reconstructed cases from previous studies. First test with a similar construct set in Karlstad where the results are found to be similar. The second test with a study in Reading with a different construct found the difference between the measures as expected. The operational model's utility is demonstrated through the analytical framework in two case study experiments set in Manchester.

This study contextualises a space-time approach for architecture to analyse and think about the possibilities of travel activities facilitated and constrained by alternative urban conditions as part of a city design process. The analytical construct aligns with activity-based travel analysis in transport geography, social sequence analysis, and GPS activity data analysis in geography. Thus, the analytical construct enables a conceptual link between applied research and fundamental research in understanding cities' functioning and evolution. The analytical construct provides a foundation for further research related to system changes in the wider social context that substantially modifies everyday travel-related activity patterns and how city design of alternative urban conditions can respond to changing circumstances.

Keywords

Future built environment, travel activities, travel mode, space-time constraints, daily activity pattern, spatial configurations, methodological development, sustainable accessibility

Introduction

Overview

This study adopts a constructive research as an overarching framework. This research framework allows the development of new methods, tools and techniques aimed at applicability beyond a single case study. It is a research process enabling the production of innovative constructions intended to contribute to a wider real-world problem (such as climate change) and to address domain-specific needs (the need to understand the implications of alternative urban conditions in transport-integrated city design) and in so doing make a contribution to theory.

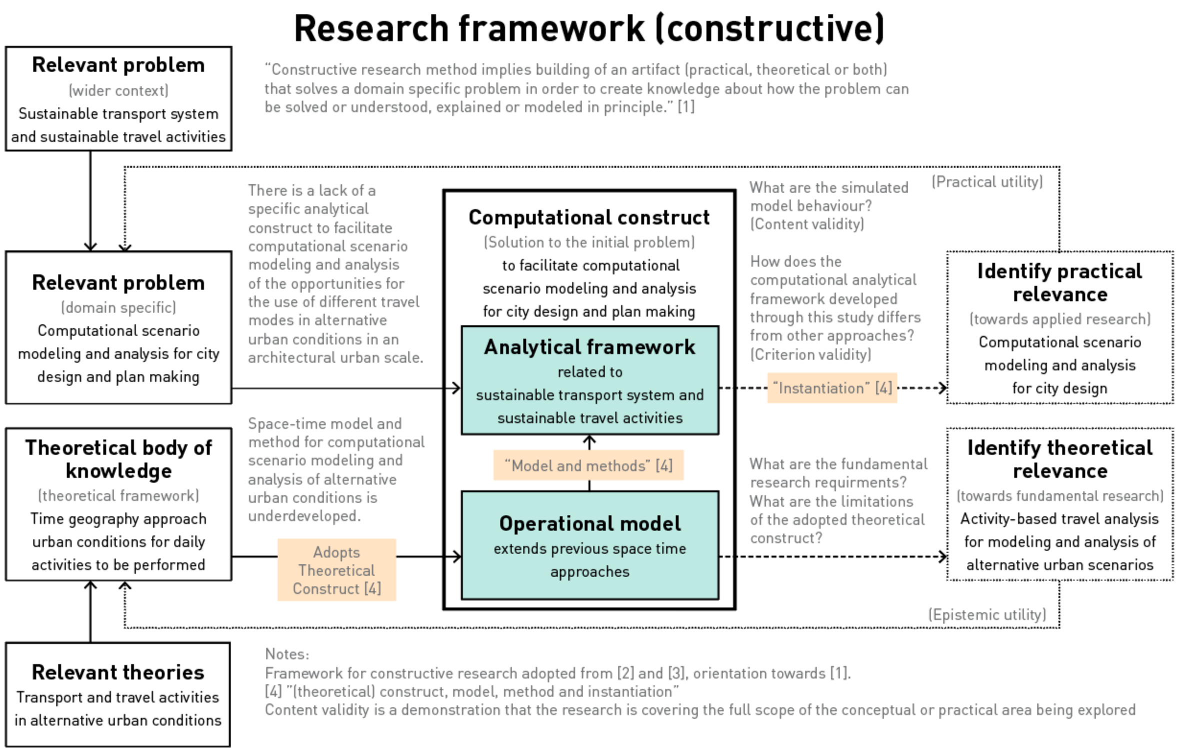

Figure 1 Framework for constructive research methodology towards info-computational knowledge generation, a combination of Dodig-Crnkovic (2014) view on "computational models and simulations" as constructive research and Kasanen and Lukka (1993)

The wider problem

The need for sustainable transport systems and to support sustainable travel activities is widely acknowledged to be a real-world problem. The transport sector is a major contributor to greenhouse gas (GHG) emissions that has a substantial global environmental impact in terms of climate change as well as local environmental impact of air pollution. The challenge in a sustainable transport system for the movement of people is to fulfil the travel needs of the population while minimising environmental impact.

The domain-specific problem and practical relevance

The transport integrated city design involves considerations in spatial functions and transport systems. Spatial functions and transport systems are interdependent and influences travel activities within a city.

City design processes can be “informed by more rigorous and objective methods” (Karimi, 2012) and supported by analytical methods (Bertolini, le Clercq and Kapoen, 2005).

There are multiple analytical approaches currently employed for the analysis of alternative city designs related to sustainable transport systems and to support sustainable travel activities. Different analytical approach has different considerations in terms of what is included, spatial scale of interest and analytical result of interest.

The current analytical approach in city design is limited in the understanding of passenger transport. An understanding of passenger transport within a mix of other travel modes is essential to sustainable transport systems and supports sustainable travel activities in an architectural urban scale.

There is a lack of an appropriate computational analytical constructs in architecture for the modelling and analysis of opportunities for the use of travel modes in alternative urban condition.

The research outputs from this study

The constructive research approach will be used in this study to construct a computation enabled analytical framework to the domain-specific problem and to construct a computational space time model to support the analytical framework.

The computation enabled analytical framework contributes to transport-integrated city design towards sustainable transport system and to support sustainable travel activities. Facilitating the comparison of travel modes, in particular, time-sensitive passenger transport services, for diagnostic assessments of multiple alternative future urban scenarios. The development of the computational space time model will be based on and extends the currently underdeveloped space time models for alternative urban conditions.

The theoretical relevance

The computation enabled analytical framework is based on the possibilities for the use of alternative travel modes that enables access to opportunities to undertake daily activities. The computation enabled analytical framework is supported by the development of the computational model and method which extends an established time geography theoretical framework for the analysis of access to opportunities based on daily activities (Kwan, 1998; Miller, 2005) related to activity-based travel analysis in transport modelling (Timmermans, Arentze and C.-H. Joh, 2002a).

This study contributes to the time geography framework through the construction of the underlying model and method for the analytical framework for the identified relevant problems. The main area of contribution is the underdeveloped area of space-time model and method for the analysis of alternative urban conditions towards a more sustainable transport system. The development of space-time model and method in this study presents further enhancement to the “the realism of the time-geographic approach to measuring accessibility” and “to enhance its role in the realm of transport planning and practice” through the “ease of implementation” for an analytical construct that is highly specialised with “increasingly complex algorithms” (Neutens, Schwanen and Witlox, 2011).

The contextualisation of space-time-oriented methods for city design has been informed by geocomputation and geography (Kwan, 2004a), human activity analysis (Shoval and Isaacson, 2007), activity-based travel modeling and analysis (Timmermans, Arentze and C.-H. Joh, 2002a). This provides a wider conceptual connection to established and relevant fields of research.

Significance of study

What the study will contribute and who will benefit from the study

In the UK, national and local authorities are engaged in attempts to improve the sustainability of transport systems towards achieving urban sustainability. The issue is multi-facetted, and broadly speaking, on one side there is known intent from trip makers themselves to conduct travel activities with less environmental impact (Boratto *et al.*, 2020), and related to this, there are ‘soft’ policy measures aimed at travel behavioural change. While on the other, the choices for using travel modes with less environmental impact in an urban condition are inevitability constrained by “the conditions beyond the individual” (Stern, 2000). For example, the availability of alternative travel modes between the origins and destinations of travel activities. The facilitating and constraining condition is related to spatial distribution of functional use, availability of amenities, facilities and the transport system that connects people to opportunities for activity participation.

Sustainability of transport systems and travel activities is a multifaceted topic and that is advantaged through plurality of approaches. This study is indirectly of interest to people involved in the design, analysis and diagnostic assessment of alternative urban conditions. The design, analysis and diagnostic assessment of alternative urban conditions of interest to people involved in the making and remaking of cities in terms of spatial allocation of functional use, locational decisions of amenities and facilities, intended activities in physical space and transport infrastructure.

Background

Transport systems play a major role in the environmental impact of cities and hence have a significant impact on environmental sustainability. Urban land-based passenger transportation for the movement of people, excluding aviation and freight transport, is one of the major contributors of greenhouse gas (GHG) emissions and accounts for 19% of the overall emissions in 2015 in the UK (BEIS, 2015).

Achieving environmentally sustainable transport system for the movement of people is challenging. Environmentally sustainability of a transport system depends on the amount of transport activities on different transport modes including passenger and personal transport modes. Environmental sustainability is most directly achieved through the reduction of motorised transport activities including passenger transport, but travel activities related to social and economic activities must be supported in cities. This results in a problem involving passenger transport services aimed at supporting sustainable travel activities but has environmental impact in operation.

The wider problem

It is widely acknowledged that a reduction of single occupancy car use is beneficial towards environmental sustainability through a reduction in transport activities while maintaining travel activities. It is however a challenge to achieve this goal.

The need to consider different travel modes is commonly recognised across all identified notions of transport and travel-related sustainability. In a planning context, there is a need to provide opportunities for multiple travel modes as alternatives to car use to support sustainable travel activities.

Besides multiple occupancy car use, active travel modes such as walking and cycling and passenger transport modes are the main alternatives to car use. While active travel modes have the least environmental impact with additional health benefits, it is can be impractical depending on the specific circumstances. Passenger transport modes typically enables a shorter journey time to reach destinations compared to walking. However, passenger transport modes are often motorised and thus contribute to GHG emissions. There is a need to consider the environmental viability of passenger transport.

What is being done to address the wider problem?

Policy initiatives, planning and design interventions

There are two perspectives in the attempts to achieve transport and travel-related sustainability related to a reduction of car use through policy, planning and design (1) the first perspective focuses on initiatives aimed at changing individual travel behaviour or travel practices (2) the second perspective focuses on interventions that modifies physical space, use of space and transport infrastructure.

Both perspectives are important in attaining transport/travel related sustainability. Interventions in physical space, use of space and transport infrastructure in themselves are not sufficient to reduce car use. At the same time, the physical space, use of space and transport infrastructure has a facilitating and constraining role in the possible travel behaviour or travel practice that can be performed in an urban situation. This study focusses on the second perspective, in particular, in the context of plan making.

Research motivation: The problem in practice

Alternative urban conditions and scenario analysis

Multiple initiatives or interventions can be proposed that are said to contribute to transport/travel-related sustainability. However, not all alternatives have the same implications towards transport/travel-related sustainability. There is a need to analyse and assess the differences in alternative proposed urban conditions. A diagnostic assessment of the potential performance and effectiveness of alternative proposal can be used to improve the proposals in a city design and plan making decision making process (Bertolini, le Clercq and Kapoen, 2005). A summative assessment can be used to evaluate different merits of alternative proposals in a higher-level plan making process (Dodgson *et al.*, 2009).

Computational scenario modelling and analysis is a method to analyse alternative urban conditions. While there are many different conceptualisations of scenario modelling and analysis, this study refers to computational scenario modelling and analysis for the purpose of diagnostic assessment of alternative urban scenarios to support design processes (Lima, Kos and Paraizo, 2016). In this context, scenario modelling involves setting up a baseline condition and alternative urban conditions. For the purpose of urban-transport scenario analysis, an example of a baseline condition is an existing urban condition consisting of the spatial distribution of functions, transport infrastructure as well as other parameters depending on the analytical approach. Alternative urban conditions include proposed options, for example, the introduction of a new development or a new transport service.

A computational analytical procedure is performed on the baseline condition results in a baseline scenario. The same analytical procedure is performed on the alternative urban conditions resulting in alternative scenarios. The relative differences in the outputs between the baseline scenario and the alternative scenarios provides the results for interpretation and assessment.

There are studies using computational scenario analysis to study alternative urban scenarios towards different notions of transport/travel sustainability. However, most studies in academic literature are aimed at a regional scale. There are limited studies at an architectural urban scale with a level of detail applicable for local development, intervention and city design.

The problem in computational scenario analysis for city design in architecture

Approaches to analytical procedures within computational scenario modelling of alternative urban conditions depends on the underlying theoretical conceptualisations of the subject

What can be interpreted or assessed from a scenario analysis depends on the approach adopted for the underlying analytical procedure that relates urban conditions to conceptualisations and theories of potential transport or travel activities. The analytical procedures are made possible through models and methods that operationalise theoretical conceptualisations. In this context, “model” refers to a systematic representation (Ozel, 1993) of land and transport system and includes the interactions within the systems represented in terms of the way they function (Lowry, 1965) as symbolic mathematical models and logical rule-based models (Batty, 2017).

The problem of input sensitivity
It is widely acknowledged that "all models are wrong but some are useful" and models have an inherent map-territory relation to the real world. In short, a model ceases to be useful when it is an exact replication of the real world, elements are necessarily abstracted or reduced and thus there is a fundamental question of input sensitivity for design/policy – if the model does not accept certain possible changes as inputs, the implications of possible changes cannot be examined.

The conceptualisations and theories underpinning the analytical approaches indicate the range of inputs possible and thus implications on the sensitivity to spatial policy and design questions. Hence, there is a need to evaluate the underlying analytical approaches for urban-transport scenario analysis and identify their relationship to different notions of transport/travel sustainability and its relevance for the analysis of different travel modes.

Three broad approaches to analytical procedures for the analysis of potential transport/travel activities in alternative urban conditions
There are **three broad approaches** based on different conceptualisations and theories of potential travel activities in alternative urban conditions:

1) **Metrics of urban characteristics** to indicate probable outcomes
2) **Transport models (model of urban systems)** to estimate probable transport/travel activities
3) **Accessibility-based approaches** to delimit the possibilities of movement and access to opportunities
(see chapter 3 theoretical framework for a detail discussion)

The relationship between the domain-specific problem in computational scenario modelling and analysis and the wider problem of sustainable transport system
Relationship between the three broad approaches to transport/travel-related sustainability
The three broad analytical approaches identified relates to different aspects of transport and travel-related sustainability.

1) **Metrics of urban characteristics** to indicate probable outcomes
This approach provides useful insights specific to pedestrian and vehicular movement patterns through probable patterns of people movement given an urban condition contributes to the design process for "walkability" and "street as a space" both of which are related to the **people-focus aspects of sustainable mobility** but they are limited in the study of passenger transport as a travel mode, which is not useful for the focus of my research in the comparison of travel modes in alternative urban conditions.

2) **Transport models (model of urban systems)** to estimate probable transport/travel activities

This approach provides useful insights in the **estimation of the amount of transport activities**. Estimated amount of transport activities by different travel modes contributes to the process of estimating amount of GHG emissions associated to transport activities. There are known procedures to estimate the amount of transport activities by different travel modes. The process of estimating the modal split essential to separate the estimation of the amount of transport activities by different travel modes depends on the formulation of the estimation process. The process typically includes (1) travel time and cost and (2) the formulation of a "choice set" as a set of alternatives supported by different travel modes between an origin and destination pair. However, there are no standard specifications in the formulation of "choice set" between opportunities, which is complimentary but different from the focus of my research in the comparison of travel modes in alternative urban conditions.

3) **Accessibility-based approaches** to delimit the possibilities of movement and access to opportunities

Accessibility in this context refers to the ease of access to opportunities distributed across space, and in some formulation, time. Accessibility-based approaches enables the analysis of existing and alternative urban conditions by delimiting the possibilities of movement and the access to opportunities by different travel modes. The distribution of accessibility in alternative urban conditions meant that the set of alternatives to travel between opportunities supported by different travel modes can be assessed. This contributes to the understanding of the availability of alternative travel modes across a geographical area to support sustainable travel activities.

Out of all three approaches, accessibility-based approaches are closely aligned with the research motivation in supporting scenario analysis for the wider problem of transport integrated city design to support sustainable travel activities.

The problems of accessibility-based approaches in the context of the problem of computational scenario modelling and analysis for city design.

There are multiple conceptualisations of accessibility and operationalisations of accessibility. There is no single definition of urban accessibility (Rietveld and Bruinsma, 1998). "There are no universally acknowledge definition of accessibility indicators with different theoretical backgrounds, proposed and implemented in empirical investigations" (Baradaran and Ramjerdi, 2001). With an aim towards "sustainable accessibility", there are "a number of specifications, calibration, interpretation issues that need to be address" (Bertolini, le Clercq and Kapoen, 2005) in the selection of an accessibility measure for a specific local area.

There are two broad perspectives in the conceptualisation of accessibility (1) location-based accessibility and (2) person-based accessibility.

Location-based accessibility are "functions of locations rather than people" (Miller, 2005). They are particular useful in decision contexts where the spatial distribution of facilities locations and functional land use such as residential and commercial are the focus.

Person-based accessibility enables the inclusion of the considerations of people in accessibility analysis as “a flexible approach that can accommodate accessibility of people to people as well as people to places” (Miller, 2005). Differ to location-based approaches, can “reveal differences in individual accessibility” with respect to different population groups in different urban conditions (Kwan, 1998).

Miller (2007) suggested “person-based accessibility”, in particular, “space-time accessibility” as a complementary approach to commonly used “location-based accessibility”. The need for further research in “person-based accessibility” is recognised (Iacono, Levinson and El-Geneidy, 2008).

The procedures to compute space-time accessibility relies on model and methods with associated theoretical constructs derived from time geography. This is referred to as “space-time model” in this study. There are two different types of studies that constructs and make use of space-time model (1) to produce space-time accessibility measure of an existing condition for further analysis and (2) for simulative studies to analyse and assess existing and alternative urban conditions.

“Space-time accessibility” as a specific analytical formlations of metrics (Miller E, 1991; Kwan and Hong, 1998; Neutens et al, 2007) and its underlying “space-time model” has been formulated and elaborated in multiple studies for the purpose of assessment and empirical studies (Kwan, 1998; Kim and Kwan, 2003; Soo 2009; Charleux, 2014).

There is an underdeveloped area of the underlying space-time model for the purpose of developing alternative urban conditions within a city design process. Previous work includes PESASP (Lenntorp, 1976), MASTIC (Dijst, 1995) with most recent example of an instantiation of MASTIC to study an urban area in 2003.

Domain specific problem definition

Attaining a sustainable transport system and to provide support for sustainable travel activities is a desirable goal in city design. City design involves the production of alternative urban conditions in the form of prospective proposals that are yet to be part of the real world. How prospective alternative urban conditions supports certain desirable goals is a common question in design decision making processes.

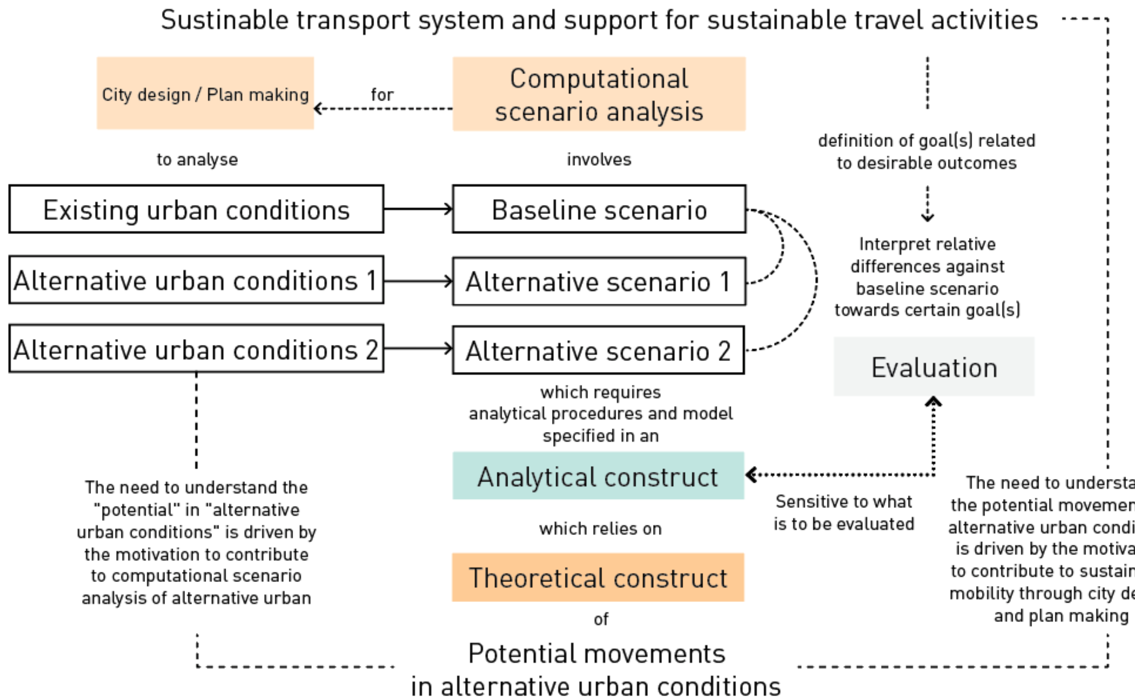

Figure 2 Relationships between scenario analysis, alternative urban conditions and analytical construct

Computational scenario modelling and analysis provides model-based reasoning and evidence for a specific assessment question. Computational scenario modelling and analysis is a method that facilitates the analysis and assessment of alternative urban conditions for city design.

There are differences between analysis, assessment and evaluation. In this study, “analysis” provides information on the differences between alternative urban conditions, “assessment” involves diagnostic formulative value judgement on alternative urban conditions based on the results from analysis and “evaluation” involves summative value judgement on alternative urban conditions.

Computational scenario modelling and analysis of alternative urban scenario relies on computational analytical procedures. What can be analysed in scenario analysis depends on the analytical approach and what is included in the computational analytical procedures. What can be assessed from a computational scenario analysis depends on the analytical outputs from scenario analysis.

An analytical framework bridges between analysis and evaluation of alternative urban conditions. A computational analytical framework sets out the analytical process from the inputs of what are included and what can be modified to the outputs of what can be analysed from alternative scenarios. Computational analytical framework requires computational analytical procedures to transform inputs to outputs. This transformation from inputs to outputs is dependent on the analytical approach.

Computational analytical procedures rely on computational analytical models that includes parameters sensitive to the analytical procedures. Computational analytical procedures to analyse alternative urban conditions towards evaluative goals and computational analytical model has to be developed together as a computational analytical construct.

Research gaps

1. Research needs in relation to domain-specific problem

There is a lack of an adequate computational analytical framework that considers new urban developments and new transport services in the analysis of alternative urban scenarios. In particular, in terms of the comparison of travel modes in combination of new urban developments. A space-time analytical approach theoretically supports the analysis of travel modes in alternative urban conditions. Previous examples of space-time models have demonstrated the possibilities for the use of a space-time analytical approach for the comparison of travel modes. However, the development of model and methods for alternative urban conditions is underdeveloped.

2. Research gaps in relation to methodological development as constructive research

2.1 Space time models for alternative urban conditions

There is an established line of research in space-time models to anticipate the possibilities of movement in urban conditions with multiple possibilities of human actions facilitated and constrained by the physical space, use of space, transport infrastructure and transport services. There are limitations in the formulations that requires further development which will be explained in detail later in the document. In particular, "space-time model" aimed at alternative urban conditions.

2.2 Develop stand-alone procedures for space time models

Space-time accessibility relies on analytical constructs that is highly specialised with "increasingly complex algorithms" (Kwan and Hong, 1998; Kwan, 2004a; Neutens, Schwanen and Witlox, 2011). Recent work on space-time accessibility typically develops the analytical construct with an emphasis for empirical studies purposes. They are usually developed on top of existing commercial Geographical Information System (GIS) packages (Charleux, 2015) that is difficult to specify the inputs of alternative urban conditions in a city design context. Neutens et. al. (2011) has pointed out the need "to develop stand-alone, open-source" procedures that are completely independent but compatible with popular commercial GIS packages.

2.3 Space time models for time-sensitive passenger travel modes

Although the representation of the transport system within space-time models has evolved over time with increasing fidelity, there remains a lack of methods that includes passenger transport as a travel mode that is time-sensitive. Related work MASTIC in past literature as a space time model provides a conceptual basis for the comparison between different travel modes in alternative urban conditions with considerations of interpersonal differences (Dijst, de Jong and van Eck, 2002; Ritsema van Eck, Burghouwt and Dijst, 2005). However, it is limited in the representation of the transport system.

Research aim

The aim of this study is to develop a computation enabled analytical construct as a method to facilitate diagnostic assessment of alternative urban conditions for transport-integrated city design. The process taken to develop the analytical construct and the analysis of the analytical construct developed aims to the identify implications for applied research towards practical utility and implications for fundamental research towards epistemic utility.

Research objectives

Table below maps the research objectives in this study aligned to steps in a constructive research approach.

CRA steps	Objectives	Relevant sections
Find a practically relevant problem that also has research potential	Conduct literature review on current approaches to GHG emissions reduction in transport	Background: Climate change and transport Problem in the wider context: sustainable transport system and sustainable travel activities
	Conduct literature review on current approaches in city design towards sustainable transport system and to support sustainable travel activities	Background: City design Domain-specific problem: Current analytical approaches are limited to facilitate computational scenario modelling and analysis for city design
Obtain a general and comprehensive understanding of the topic	Conduct an overview literature review on how travel behaviour is conceptualised	Overview of literature on travel behaviour
	Conduct state-of-the-art review on current computational analytical constructs for the modeling of potential transport and travel activities in alternative urban conditions	State-of-the-art review
	Analyse analytical approaches and their associated theoretical frameworks related to future transport and travel activities	Comparison of three analytical approaches: metrics of urban characteristics, transport

		modelling and space time approach
	Define theoretical framework and theoretical contributions for this study	Theoretical framework
Innovate (i.e. construct a solution idea)	Construct an operational digital model and methods extending previous space-time model approaches with specific attention to the ability to examine alternative urban conditions	Operational model: design and implementation
	To develop digital model for the inputs of the opportunities of activity participation, transport infrastructure and time-sensitive passenger services	Constructing urban conditions
Demonstrate that the solution works	Test the structure and model behaviour of the analytical construct through multiple scenarios (demonstrate construct effectiveness)	Case study experiments • Interpretation of results
Show the theoretical connections and the research contribution of the solution	Provide evidence of criterion-based validity	Criterion-based validity • Construct convergent validity • Construct discriminant validity
Examine the scope of applicability of the solution	Interpretation of results from case study experiments drawing connections to the literature	Discussion • Implications for applied research related to transport-integrated city design • Implications for fundamental research related to the analytical approach

Table 1. Steps in constructive research approach informed by (Kasanen and Lukka, 1993) with author's own relevant sections identified in this study

Research questions and summary of knowledge claims

Primary questions

1. How can space-time model be extended incorporating new technologies and data sources for ex-ante (before the fact) analysis of alternative urban conditions?

Knowledge claim 1: Improved known method and model incorporating new technologies for the analysis of person-based accessibility in alternative urban conditions

2. How can a space-time computation-enabled analytical construct facilitate scenario modelling and diagnostic assessment of alternative urban conditions toward sustainable transport systems and to support sustainable travel activities?

Knowledge claim 2: Demonstrated application for the improved method in the context of opportunities for travel mode change in alternative urban conditions

Secondary questions

3. What is the current available knowledge about transport-integrated city design toward sustainable transport systems and to support sustainable travel activities?

    a. How is GHG emissions reduction in urban transport conceptualised?
    b. What are the current approaches to GHG emissions reduction in urban transport?
    c. How can city design contribute to sustainable transport systems and to support sustainable travel activities?

4. What are the theoretical knowledge and considerations to support an appropriate computational analytical construct for ex-ante analysis of alternative urban conditions towards sustainable transport systems and support sustainable travel activities?

    a. What are known conceptualisations of transport and travel analysis in academic literature? (literature review Chapter 2 section 1)
    b. What are the analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions? (literature review Chapter 2 section 2)
    c. How do the analytical approaches relate to notions of transport/travel-related sustainability? (literature review synthesis and conclusion)

Knowledge claim 3: Shed some light on current analytical approaches for 'before the fact' analysis in relation to notions of sustainability relevant to travel activities in alternative urban conditions within built environments

Contribution to knowledge

This study has a primary focus in methodological development where the potential of a space-time approach for scenario modelling and analysis on alternative urban conditions for city design is explored through a constructive research framework.

The main contribution to knowledge derives from the development of an analytical construct in two parts (1) further development of space-time model for alternative urban condition within a time geography theoretical framework (knowledge claim 1) and (2) an analytical framework to compare travel modes in alternative urban conditions (knowledge claim 2).

The process taken to develop the analytical construct and the analysis of the analytical construct developed leads to the identification of **implications for applied research** towards practical utility and **implications for fundamental research** towards epistemic utility.

The research output and object of the study is the analytical construct developed in this study. This study adopts the views of Winter (2008), March and Smith (March and Smith, 1995) from information system-oriented design research as a useful framework to facilitate the description and understanding of different elements within artificial constructs, its connection to the theoretical analytical approach and its connection to facilitate applied scenario analysis.

"Construct, model, method and instantiation" (March and Smith, 1995) are four well-known types of research outputs from constructive-oriented research. Construct, in the sense of theoretical construct, forms the "vocabulary of a domain" and "conceptualisation used to describe problems within the domain and to specify their solutions". This includes the presumptions, conceptualisations and entities to be included. Model consists of an operational set of propositions expressing relationships between conceptualisations and entities. Method refers to a set of steps used to perform a task, for example, algorithms. Instantiation is defined as "the realisation of artefact in its environment" (March and Smith, 1995). Artificial constructs make use of "kernel theories" that are theories from design, natural or social sciences (Hevner and Chatterjee, 2010).

The **computational analytical construct** developed in this study is evaluated in two ways (1) as a **computation enabled analytical framework** to analyse the possibility for the use of different travel modes under different urban conditions and individual's space time constraints. This is **demonstrated through examples** of the analytical construct for scenario analysis as use cases and contributes to **identify its implications for applied research**. (2) the underlying **computational model and methods** for the analytical framework is compared against model and methods known to be similar and different for its construct convergent and discriminant validity respectively and to **identify its implications for fundamental research**.

This study adopts the theoretical constructs from time geography and person-based accessibility as “kernel theory” (Hevner et al, 2004) to develop the analytical construct as model and method for the analytical framework to examine opportunities for the use of travel modes based on daily activities.

A time geography approach is explored in this study as a “kernel theory” that supports a space-time analytical approach for scenario analysis of alternative urban conditions. This is supported by a literature review on theoretical knowledge and considerations that underpins computational analytical construct to facilitate scenario modelling and diagnostic assessment of alternative urban conditions towards sustainable transport systems and to support sustainable travel activities. (research gap 1, 2.1, knowledge claim 3)

The developed analytical construct is theoretically based on previous literature relevant to this study including PESASP (Lenntorp, 1976) and MASTIC (Dijst, 1995). PESASP (Program Evaluating the Set of Alternative Sample Paths) is the first operational model of space-time theoretical constructs. It is widely cited in activity-based travel analysis and person-based accessibility literature that relates the physical environment and human daily activities. The model includes the formulation of an analytical framework, operational model and instantiation to enumerate the possibilities (simulated sets of alternatives) for an activity programme (daily time schedules of activities with duration) to be performed within a given urban condition.

This study extends previous space-time model to examine alternative urban conditions with contemporary technological procedures and available datasets. For the purpose to assist city design assessment of alternative urban conditions. Specific attention is given to the ability to alter inputs to describe alternative urban conditions for the analytical construct. In particular, the ability to analyse and compare new passenger transport services with other personal travel modes in alternative urban conditions. (research gap 2.1)

The space time theoretical construct developed by Lenntorp (1976) sets out the relationships between activity programmes, opportunities of activity participation, transport network and services. The subsequent relevant work in space-time model for the simulation of space-time prisms (such as MASTIC) and for person-based accessibility (Villoria, 1989; Kwan and Hong, 1998; Soo, Ettema and Ottens, 2009) largely follows a similar theoretical construct. The ability for the analytical construct to study alternative urban conditions is underdeveloped. The analytical construct developed in this study addresses the three identified research gaps.

One of the main challenges is the reliance on proprietary GIS software packages where proprietary space-time procedures are constructed in recent literature. The representation of transport system in this study differs from previous approaches to space-time model. This study incorporates a contemporary open-source multi-modal router OpenTripPlanner (OTP) which includes passenger transport and personal travel modes that is able to work with common data standards (OSM and GTFS) with wide availability of dataset and supports multi-modal routing including transfers between different travel modes. The use of GTFS enables a time-sensitive description of passenger services. (research gap 2.2, 2.3)

A set of computational tools has been developed to assist in the alterations to the underlying geographical data (OSM) and computational description of passenger services (GTFS) to assist with the city design process. (research gap 1,2)

Implications for applied research

This study describes three implications for applied research (1) current analytical approaches for transport-integrated city design towards sustainability of transport system and sustainable travel activities (2) recontextualise underexplored space-time approaches for transport-integrated city design, and (3) exploration of properties of the analytical construct in alternative urban conditions.

Implications for fundamental research

The applied orientation of the analytical construct creates the link between specific types of fundamental research in studies of the elements that contributes to understand the functioning of cities (Batty, 2008b) and applied research for city design in general (Karimi, 2012) and more specifically with a space time approach (Pickup and Town, 1981; Ritsema van Eck, Burghouwt and Dijst, 2005).

Chapter 1 - Background

1.1 Chapter introduction

This study is undertaken within the School of Architecture. As Groat and Wang point out, research in architecture is inherently plural, multifaceted, and diverse (Groat and Wang, 2013). There are other notions of what constitutes architectural research (de Sequeira, 2011) ranging between different foundations and methodological orientations (Lucas, 2016), including different epistemological orientations (Jensen, 2010) and discussions, specifically in architectural design research, in computational exploration of material systems at a building scale (Weinstock, 2008). In a larger scale of urban planning, planning research methods are equally plural and diverse (Barry, 2014).

This section attempts to clarify the research motivation of this study, (1) the wider context of urban development, urban movement, climate change, different notions of sustainability of urban movements, in which this study is situated, and (2) the topic of investigation to understand changes in the built environment towards desirable goals of sustainability (3) through a specific research interest in spatial analytical computational modelling within this wider context and topic.

This section concludes with a statement of the position of this study and to clarify the aim to construct an analytical framework and operational model.

1.2 Urban environment and human induced changes in urban environment

This study has been conceived with an underlying interest in the **urban environment** that "encompasses patterns of human activity within the physical environment" (Handy *et al.*, 2002) and **human induced changes** or alterations to the urban environment. More specifically, coordinated or individual plans/decisions to **change** the urban environment that are part of urban planning and design.

There are many conceptions of planning and design in an urban context such as "spatial development", "spatial planning", "land use planning" (Nadin, 2006), "policy design", "service design" and "urban design". Although there are many variations, there are commonalities between different conception. In general terms, planning and design typically involve decisions that lead to intentional actions which result in direct or indirect changes in the urban environment.

Another thing in common interest in planned and designed human-induced urban change is that they are usually indented towards desirable goals that are deemed to be of value. Desirable goals can be as wide as sustainability with various definitions or specified and defined as something measurable such as the amount of fuel consumption per capita within a specified unit of analysis such as cities (Newman and Kenworthy, 1989).

The interest of this study in intentional changes in the urban environment has two parts (1) coordinated or individual plans/decisions that produce alternative urban condition, (2) desirable goals.

1.2.1 Design/planning as plans/decisions to change an urban environment towards desirable goals

The first part involves “coordinated or individual plans/decisions to change an urban environment”. It is possible that the word “plans” invites domain-specific reading and interpretations, especially in architecture, where it implies design or as a set of drawings. There are multiple meanings to the word “plan” as a verb, “to think about and decide” what to be done or how something is going to be done with an emphasis on decision, “to think about and decide on a method for doing or achieving something” with an emphasis on method and “to design a building or structure” in terms of design (Cambridge Dictionary Online). Design/planning disciplines such as spatial planning, urban planning, transport planning, urban design and architecture as well as urban policy and transport policy that influences design, planning and changes in the urban environment can be related to these three meanings of “plan” to various degrees in different contexts. In different contexts, the boundaries of decisions (in other words, the amount of control over what can be done) and what is to be achieved (goals) differ.

The act of design and/or planning to develop plans in a broad term as decision/method/design to change an urban environment is usually associated with various design/planning disciplines. It typically involves coordinated collective decisions – a typical urban scale project in the UK may involve architects, landscape designers, structural engineers, highway agencies, planning consultants, environmental consultants, planning authorities, highway agencies, building contractors, clients, funders, stakeholders, and the public. The boundary of decisions for changes in the urban environment is often limited to the ownership of the project site and its immediate surroundings.

It is possible for changes in the built environment to be made without the involvement of design/planning disciplines that design the changes. This may, for example, be the case, where the urban processes of spatial change are entirely market-driven, unregulated, uncontrolled (Clark, 2013), or derived from bottom-up processes such as informal settlements (Patel, Crooks and Koizumi, 2012). The point is, while there can be limited involvement of design/planning disciplines in such situations, there are still individual (individual/household/community) plans set out to change the built environment. These individual plans may not have a plan in design terms, but at the very least, the decision has to exist, for there will be no human-made changes in the built environment.

On the other end of the spectrum, there are decisions related to the urban environment from a higher level, not limited to individual sites. These are usually found in the form of polices – spatial policy, land use policy, transport policy – that may not directly plan for specific changes in the urban environment but indirectly influence the way in which changes may occur - for example, through policy interventions, initiatives, and regulatory instruments (Krott, 2005).

This study refers to plans to change the built environment as potential decisions/instruments/interventions/initiatives that are conceived or can be conceived but are yet to be implemented, and are intended to directly/indirectly modify/induce/influence changes in an urban environment that encompasses patterns of human activity within it. The wider question, too wide for this study to answer but useful for discussion, is how can different forms of plans/decisions at multiple levels towards changes in the urban environment be directed towards desirable goals and what are the roles in the plans/decisions at an architectural urban design level?

The second part is desirable goals and the relationships between plans to change built environment and desirable goals. There can be different understandings of desirable goals, following on from the previous part that outlines the three plan/decision-making levels. For urban policy, the system of planning aims to "direct it towards socially desirable goals" as well as "the identification of desirable goals for urban development often aimed for the public good, "specification of the steps necessary to reach them" and "monitoring and evaluation" (Clark, 2013). On the other end of the spectrum, there are personal values that guide personal desirable goals, such as "self-direction, stimulation, hedonism, achievement, power, security, conformity, tradition, benevolence, universalism" (Schwartz, 2012).

The identification and formulation of common desirable goals given that there can be different presumed values is a challenge outside the scope of this study. This study focuses on a commonly acknowledged urban challenge - to attain urban sustainability as the wider desirable goal and the notion of sustainable development and sustainable accessibility that corresponds to the topics of urban development and urban movements. The identification of personal values and goals is beyond the scope of this study, but relevant to this study and will be discussed in a later section (pg31-32) as an inseparable part of a desirable goal of sustainable accessibility, more specifically with environmental impact in terms of greenhouse gas (GHG) emission reduction while meeting the desire/needs/wants/commitments of personal urban travel and movement. The later section will describe the current ways in which GHG emissions for land-based travel are quantified. By extension, known ways to numerically understand the environmental impact of personal movements from a people-based perspective, and how it differs from a city level view of GHG emissions will also be discussed (section 1.4.7.2 pg56).

The possibility for attaining desirable goals such as a reduction of GHG emissions while maintaining activities made possible by transport/travel activities in the urban transport/travel context requires decisions from a spectrum of decision makers/actors illustrated in the following simple example. First, assume there is a decision on whether to introduce a new bus service. A plan/decision to provide a bus service does not immediately result in a reduction of GHG emissions at a city level; it remains as an intent. Assume a new bus service is operational in service, the introduction of a bus service does not in itself reduce GHG emissions, but it is likely to have increased GHG emissions at a city level assuming the vehicles providing the bus services are motorised, which consumes energy, and all other travel activities stay the same – the bus services is an addition to the transport activities. Therefore, a reduction of GHG emissions at a city level, made possible by a new bus service, can only be achieved through a reduction of the number of personal vehicles – a reduction in overall transport activities – where people who would have driven, utilise the new bus service instead. The last point relies on the decision of the potential users of the bus service.

There are two possible emphases in research between environment and people: (1) an emphasis on the study of decision makers/actors in relation to the environment or (2) a focus on the role of the physical and functional urban environment in relation to people. This study focuses on the role of the physical and functional urban environment and its relation to people as decision makers/actors within the urban environment, which will be discussed and clarified later, first through the differentiation of transport activities and travel activities (see section 1.5.2.1 pg34).

This study takes the view that the urban environment does not determine travel activities (determinism) that are associated to wide desirable goals of GHG emissions reduction. By extension, changes in the urban environment do not determine travel activities (architectural determinism). However, the urban environment has a role in facilitating and constraining the possibilities for different kinds of travel activities (possibilism). As a result, change in the urban environment creates opportunities for different kinds of travel activities (architectural possibilism). The conceptual relationships between people and the environment will be further discussed in a later section (section 3.2 pg113).

1.2.2 Intended changes are typically limited: a subset within a wider context

Models of (weak) emergence have the property of a collective of small changes from multiple decision units over time that produces a larger pattern that can be recognised. This view is relevant to planning because from a high-level planning point of view, under a complexity framework, control is often limited to the guidelines and providing conditions for small changes at the micro level. The difficulty in planning for certain kinds of desirable outcomes is that the desirable outcome relies partly on factors that are beyond the direct control of planning. It is useful to understand whether the guidelines and conditions can steer urban situations towards a desirable outcome at the level of the larger pattern over time.

1.2.3 Spatial design and planning

Spatial planning needs to build an "understanding of critical spatial development trends and drivers, market demand and needs, and the social economic and environmental impact of development" as well as "generation of alternative plans and option assisted by analysis" (Nadin, 2006). The latter corresponds to the role of urban spatial design, where alternatives and options for urban developments are produced.

1.3 Sustainability and Sustainable development

The topic of movements of people in a future urban context concerns both spatial design (or disciplines that are interested in interventions/initiatives that directly or indirectly modifies/induces/influence changes in physical and/or functional space) and research. It is also known to be related to a broad and common goal for sustainable development towards urban sustainability.

There are various conceptions as strong/weak, descriptions and representations of sustainability typically as three interconnected pillars/dimensions of social, environmental and economic depicted in different ways (Purvis, Mao and Robinson, 2017). There are plural ways in which sustainability has been framed and investigated in different contexts (Kudo and Mino, 2020). This study does not aim to re-iterate the long-standing debate on “what is sustainability” (Kuhlman and Farrington, 2010). Instead, it aims to focus on notions related to the built environment, in particular, within the topic of urban movements of people and the role of architecture/urban/spatial design/policy/planning in urban transition and urban transformation. This includes physical spatial transformation and urban development, while acknowledging that there are plural ways in which sustainability can be conceived, interpreted, and valued.

Urban transition and urban transformation are notions related to “patterns and dynamics of change linking cities and diverse socio-technical and social-ecological systems across levels and scales, and develops new forms of intervention to foster their sustainability” (Wolfram, Frantzeskaki and Maschmeyer, 2016). Although there is no clear distinction between “transition” and “transformation” in literature, as Wolfram et al. (2016) point out, “transition” and “transformation” are semantically different. “Transformation” indicates “both the process and the outcome of attaining a different system configuration” and “transition” only refers to the process of attaining a different system configuration.

The notion of sustainable development is different from but related to the notion of sustainability. “Sustainable development” is “both a normative goal and process” (Wolfram, Frantzeskaki and Maschmeyer, 2016). “Sustainability” refers to the value of being able to “withstand or adapt to endogenous or exogenous change indefinitely” (Dovers and Handmer, 1992), and there are different values. There is a debate around whether sustainable development (as a normative goal and/or process) should adopt a strong or weak notion of sustainability (value) (Pelenc and Ballet, 2015).

“Urban sustainability” is a multifaceted notion that relates sustainability to cities or urban areas (in broad terms), explored in different ways. For example, as a whole system with an ecosystem approach (Bodini, Bondavalli and Allesina, 2012), studies that focus on the “equity conditions” (Vojnovic and Darden, 2013) and assessment framework (Zellner *et al.*, 2008).

1.3.1 Sustainable development

The National Research Council refers to the need to progress towards the goals of meeting human needs and preserving “life support systems”. Broadly defined, this refers to the planet’s resources that support life such as atmosphere, water and food. The UK government has adopted the 1987 definition from the Brundtland Report. This states, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland *et al.*, 1987).

1.3.2 From global SDG to Local implementations

United Nations (UN) Sustainable Development Goal (SDG) sets a set of global goals, targets, and indicators towards sustainable development in a national-global level. The UN SDG (Sustainable Development Goals), specifically the SDG 11 on cities and communities, that seeks to “make cities and human settlements inclusive, safe, resilient and sustainable” and SDG 13 on climate action, seeks to integrate climate change measures into national policies, strategies and planning (UN, 2015). SDGs cross multiple domains and are said to be interconnected and contain indivisible, reinforcing, enabling, consistent, constraining, counteracting and cancelling relationships across different goals and disciplines (Nilsson, Griggs and Visbeck, 2016). SDG is primarily a global level agenda that operates at a national level. Its implementation requires policy and planning of projects, plans and strategies at the local level (UN, 2017). More specifically, in response to SDG goal 11 target 2 “to provide access to safe, affordable, accessible and sustainable transport systems for all by 2030” (UN, 2015) where there is an agenda for DfT “to connect people and places, balancing investment across the country” (UK Government, 2019). This study focuses on urban movement of people, with considerations of interrelated effects on other dimensions.

1.3.3 Notions of sustainability related to movement of people in urban environments

There are three notions of sustainability, related to the movement of people in urban environments: (1) sustainable transport/transportation (Litman and Burwell, 2006), (2) sustainable mobility paradigm (Banister, 2008) and (3) sustainable accessibility (Bertolini, le Clercq and Kapoen, 2005; Woodcock *et al.*, 2007; Curtis and Scheurer, 2010).

1.3.3.1 Sustainable transport/transportation

Litman and Burwell (2006) point out that there is “no universally accepted definition of sustainability, sustainable development or sustainable transport”. Black (Black, 1996) provides one of the early definitions of what is sustainable transport/transportation. It extends Brundtland definition for "sustainable transportation" as "satisfying current transport and mobility needs without compromising the ability of the future generations to meet these needs" and identifies that "the current transport system are not sustainable". Other authors look at more detailed elements that relate transport activities and environmental impact. Richardson (2005), with an analytical framework, focuses on factors and their relationships from transport activities towards indicators of transport sustainability. Litman and Burwell (2006) identify the wider transport impact on sustainability in terms of social, economic and environmental dimensions. Litman and Burwell (2006) identify the changing view of transport planning from that of increased mobility as “newer, faster modes that displace older, slower modes“ to considerations of multi-modality of different travel modes. They further advocate for a “parallel model” where “each mode can be useful, and strives to create balanced transport systems that use each mode for what it does best”.

1.3.3.2 Sustainable mobility paradigm

Banister (2008) identifies the different kinds of policy instruments and actions that can contribute to a reduction of environmental impact from transport and further argued for a shift in mindset from conventional transport planning and engineering to a more human-centred approach towards sustainable mobility.

Transport planning and engineering	**Sustainable mobility**
Physical dimension	Social dimensions
Mobility	Accessibility
Traffic focus, particularly on the car	People focus, either in a vehicle or on foot
Large in scale	Local in scale
Street as a road	Street as a space
Motorised transport	All modes of transport often in a hierarchy with pedestrian and cyclist at the top and car users at the bottom
Forecasting traffic	Visioning on cities
Modelling approaches	Scenario development and modelling
Economic evaluation	Multicriteria analysis to take account of environmental and social concerns
Travel as a derived demand	Travel as a valued activity as well as a derived demand
Demand based	Management based
Speeding up traffic	Slowing movement down
Travel time minimisation	Reasonable travel times and travel time reliability
Segregation of people and traffic	Integration of people and traffic

Table 2. Source: Sustainable mobility approaches in contrast to transport planning approaches from Marshall (Marshall, 2001) and Bannister (Banister, 2008)

1.3.3.3 Sustainable accessibility

A shift from a focus on increasing mobility as a transport planning goal to other conceptions is common in Litman's description of sustainable transport and Banister's sustainable mobility paradigm. While the former has an emphasis on multiple travel modes, the latter suggested accessibility as an alternative planning goal. This view is also supported by Levine et al. (Levine, Grengs and Merlin, 2019).

Couclelis (2000) points out the need to consider wider "societal change" with the relationship to an ongoing trend of the "information age" and the impact on physical movements as a case in point. There is research in the development of tools (Curtis and Scheurer, 2010) to aid discussion and decision-making through the notion of sustainable accessibility and conceptual framework for sustainable accessibility (Bertolini, le Clercq and Kapoen, 2005).

Bertolini et al. (Bertolini, le Clercq and Kapoen, 2005) describe sustainable accessibility as accessibility 'with as little as possible use of non-renewable, or difficult to renew, resources, including land and infrastructure' with an additional element of interpretations through discussions with workshop participants to locate what is deemed to be sustainable.

Although there is a common understanding of the need to understand sustainability in transport from mobility to accessibility at a high level, different authors have different interpretations of what kind of accessibility is sustainable. As Couclelis (2000) points out, one of the main questions is the notion of accessibility being a multifaceted concept, as well as the researcher's choice of a particular accessibility measure (Bertolini, le Clercq and Kapoen, 2005).

1.4 Land-based transport for the movement of people

1.4.1 What are the current situations and future trends?

1.4.1.1 Technological advancements and innovations in transport services

There is emerging academic research from different perspectives on transport-related technological advancements such as electric vehicles (Knobloch *et al.*, 2020), autonomous vehicles (Fraedrich and Lenz, 2014) and innovations in transport services such as Lyft and Uber (Zarwi, Vij and Walker, 2016) as well as studies to understand the wider context around technologies and services in terms of potential environmental impact (Wadud, Mackenzie and Leiby, 2016) and the potential benefits and threats to different groups of people (Thomopoulos and Givoni, 2015).

Outside transport but related to transport, there are ongoing discussions on technological advancements in communication that influence the need for physical travel. Information, communication and technology (ICT) (Janelle and Hodge, 2000) and its relationships with physical movements has long been studied and conceptualised towards questions of "e-commerce, flexible working hours and teleworking" (Timmermans, Arentze and C. Joh, 2002).

Some of these trends have a direct relationship to ways to reduce transport-related GHG emissions or associated areas of "green transport" within a "sustainable transport" agenda (Suchanek, 2016). This will be discussed later in this section towards the identification of a research problem at the end of this section related to passenger transport services.

The recent global coronavirus pandemic in 2020 that resulted in many countries' measures to limit movement highlights a number of points that are relevant in this study. More specifically, (1) reduction in travel activities has an impact on economic activities (2) there has been a drop in GHG emissions to the atmosphere (Zambrano-Monserrate, Ruano and Sanchez-Alcalde, 2020) (3) there is still need for travel, for example, for keyworkers and delivery and (4) there are more people working from home where possible. The situation demonstrates a real-life scenario of a high level of teleworking, although it might not be representative in a situation where economic activity is high. At the same time, public transport, or more specifically, passenger transport that is shared with multiple passengers, is under pressure given the need for physical distancing.

Although the points above are a description of the current situation, there are already ongoing discussions about how the situation might be and its effect on travel behaviour post-event. De Vox (De Vos, 2020) suggests that "people will travel less, will try to avoid public transport and might travel more actively (recreationally or in case of short distances) or by car." At the same time, while there are expectations for public transport providers to maintain a level of service, they are in a difficult financial situation (BBC, 2020). This study contributes to the discussion, though the development of an analytical framework, to assist in the rethinking of how future passenger services could be provided in connection to urban spatial design towards sustainable accessibility.

1.4.1.2 Environmental impact of land-based transport for the movement of people

Land-based transport for the movement of people contributes significantly to climate change through the direct and indirect GHG emissions resulted from energy use. Urban land-based passenger transportation, excluding aviation and freight transport, is one of the major contributors of GHG emissions and accounts for 19% of the overall emissions in 2015 in the UK (BEIS, 2015).

Transport activities from motorised transport modes are known to produce GHG emissions directly or directly through energy use. GHG reduction in transport requires **changes in transport activities in some form**. At the same time, it is generally expected that the demand for mobility will increase as the population grow (Malayath and Verma, 2013). The population of the UK is "projected to increase by 3 million" from 66.4 million in 2018 to 69.4 million in 2028 (ONS, 2019). There is a trend of ongoing mobility growth (Rodrigue, Comtois and Slack, 2016).

1.4.2 What is transport, travel, mobility, accessibility?

"Transport" is a diverse topic with related research areas including transport policy, transport economics, transport geography, transport planning and transport engineering, where "transport" is typically a direct subject of interest amongst other aspects. There are also research areas that relate their core subject of interest to transport, such as public health, with investigations in "active travel" (for example Götschi *et al.*, 2017), and **disciplines such as spatial planning, urban planning and architecture in an urban scale that are involved in the direct change or indirect influence in shaping the built environment**. The transport system is part of the built environment and the movement of people is one of the many kinds of human activities that occur within built environments (Handy *et al.*, 2002).

Given the diverse range of research related to transport, there is a variety of terms that may be used differently in different contexts. Terms such as "transport" and "travel" are sometimes used interchangeably. The following overview provides a general description of terms, notions and concepts adopted in this thesis.

1.4.2.1 "Transport" and "Travel"

"Transport" and **"transport activities"** are commonly used in transport planning, investigations in the functioning of transport systems (Hensher, 2008) and in a national level GHG emissions estimation contexts. **"**Transport activities**"** refers to the amount of transport-related activities within a system boundary of interest. It is usually associated to vehicles and typically employs units such as vehicle-kilometres (vkm) or passenger-kilometres (pkm). “Transport” in this context is also referred to as “transportation”. Byars et. al. (2017) suggested the use of “transportation” over “transport” but usage of “transport” is common in the UK (Department for Transport, 2018). It is common for studies referring to “transport” to focus on the studies of transport systems. Transport systems consist of “a number of fixed assets, the infrastructure and a number of mobile units, the vehicles and a set of rules for their operation that make possible the movement of people and goods” (Ortúzar and Willumsen, 2011, p. 4)

“Travel” and **“travel activities”** are commonly used in research studies with a focus on the movement of people or patterns of people movement in relation to other subjects of interests such as travel behaviour (Giuliano and Narayan, 2003; Harms, Gershuny and Olaru, 2018), built environment characteristics (Boulange *et al.*, 2017) and the methods to analyse travel patterns (Ettema and Timmermans, 1997). “Travel” may be associated to a specific field of “tourism”, the use of “travel” in transport-related studies is more general.

One way to understand the difference between the two is that “transport” usually refers to the movement of people that requires a **vehicle,** including private and public transport, and “travel” usually refers to an action people undertake. Studies associate with “travel” tends to focus on **personal travel** (Brand and Boardman, 2008) or **travel patterns** (Dieleman, Dijst and Burghouwt, 2002; Timmermans, Arentze and C.-H. Joh, 2002b).

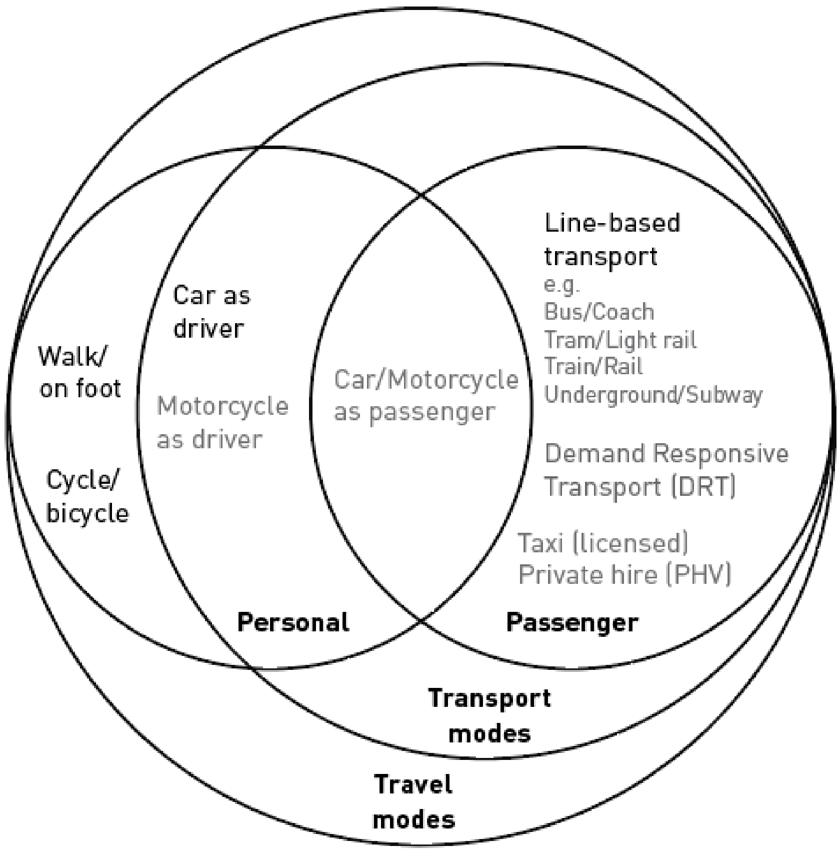

Figure 3 Transport and travel modes with examples of travel activities (author's own)

"Mobility" is a related term often used in the context of transport-related studies. Mobility has been defined "as the physical movements of people in a region. Transportation regards the means to make physical movements possible." (Poli, 2011)
Geerlings (1999) suggested one way to conceptualise the relationships between transport and mobility where "transport can be considered as the mobility of passengers and goods by traffic means to fulfil a demand. The demand of transport depends on speed, comfort, capacity, accessibility, distance, etc. Traffic can be defined as the movement of transport means including the infrastructure that facilitates mobility."

There is a further area of literature referring to "mobility" in terms of travel and movement from a wider societal or cultural perspective largely attributed to the "mobility turn" (Urry, 2002) in sociology. This is related to the topic but outside the scope of this study.

1.4.3 Urban transport/travel modes and their characteristics

There are different ways to characterise transport and travel modes. This section attempts to provide an overview of how transport and travel modes are characterised in academic and grey literature. It summarises and describes six ways in which they are characterised that are relevant to this study with examples of typical transport and travel modes.

	A		B			C		D		E		F	
	Passenger	Personal	Road-based	Rail-based	Street-based	Private	Public	Scheduled	On-Demand	Fixed routes	Flexible routes	Motorised	Non-motorised
Car	○	●	●		○	●			○		●	●	
Motorcycle	○	●	●		○	●			○		●	●	
Taxi	○	●	●		○		○		●		●	●	
Bus	●		●		○		●	●		●		●	
Train	●			●	○		●	●		●		●	
Tram	●		●	●	○		●	●		●		●	
Cycle		●	●		●	●			○		●	●	●
Walk		●			●	●			○		●		●

Table X: characteristics of typical transport and travel modes (author's own combination from multiple sources) Note 1: a basic definition of transport for use by general public Note 2: "pedal cycle" recorded as passenger transport in UK Department for Transport statistics

UK transport statistics (Department for Transport, 2018) characterise modes of travel in terms of passenger, personal and freight with greenhouse gas emissions reported for passenger modes and freight. [A]

There are different types of urban land transport by mode and its associated physical infrastructure. A typical classification is road-based transport and rail-based transport in transport planning with a focus on the functioning and performance in the corresponding transport system (Rodrigue, Comtois and Slack, 2016). Walking and cycling are often considered as travel modes in planning in the context of sustainability and transport (Kennedy *et al.*, 2005), in terms of "multimodal planning". With considerations of walking to stations as part of public transport (Litman, 2013), and associated health benefit of walking and cycling that promotes physical activity (Saelens, Sallis and Frank, 2003), "street-based" is used as a label to refer to infrastructure systems supporting personal travel activities related to "active travel" (Handy *et al.*, 2002). [B]

Modes of travel can be seen as private or public. [C] Private modes refer to the same set of modes as personal modes. A basic definition of public transport is transport for use by the general public. There can be different interpretations of what is public transport beyond the basic definition. For example, a taxi is seen as a special form of public transport and that it has a “semi-private character” (Aarhaug and Skollerud, 2014) based on the difference between taxi and conventional public transport systems.

Two simplified characteristics of conventional public transport systems as services that run on a planned schedule fixed months in advance [D], and fixed routes, for example, train services have designated routes between stations, bus services with designated bus stops and routes [E] as opposed to on-demand services such as taxi and other concepts of passenger services under the broad area of Demand Responsive Transport (Brake, Nelson and Wright, 2004), which suggests there is a range of “demand responsiveness” embedded within different passenger services.

A different way to characterise different modes of travel is between motorised and non-motorised modes commonly found in discussions for topics around sustainable transport and mobility. [F]

1.4.4 Environmental sustainability of urban movement

The environmental sustainability of urban movements can be understood in different ways. There are different issues within environmental sustainability in the context of urban mobility, including but not limited to pollution emissions, climate change, biodiversity, habitat preservation and aesthetics (Litman and Burwell, 2006).

Pollution emissions and climate change pose specific challenges in the transport sector where the transport sector is one of the major contributors to the production of emissions not only in the UK, and it has been suggested that it is also an issue in other countries (Eurostat). Pollution emissions and climate change are often mentioned together and there are overlaps between them.

However, there is a difference between the frame of reference for **pollution emissions** and **emissions contributing to climate change**. Statements on pollution emissions tend to be local with an association to local air quality highlighting health impacts, while statements referring to emission contributing to climate change tend to aim at reducing the effect of global warming.

1.4.5 What are the connections between land-based transport for the movement of people and climate change?

Climate change science – climate policy – national target – sectors – transport – land-based transport for movement of people

1.4.5.1 From climate change science to climate policy

Climate change-related sciences and policy are often related, the former as the source of knowledge and the latter related to action. As Lacey et al. (2018) points out, they are two different activities and that they are “structured and operate very differently”. Climate change-related sciences provide the evidence base but do not specify prescriptive actions; they are often “built around disciplinary specialisation and the application of particular methods or tools to specific, often tightly defined problems”. Policy, on the other hand, does not typically conduct empirical studies to measure physical climate phenomena but “deal with multiple, complex and often poorly defined or poorly bounded issues and stakeholders” (Lacey *et al.*, 2018).

Climate scientific assessments are conducted with a physical science basis, a focus on physical phenomena to provide climate change information on the impact on global regions and for risk assessment. Climate science provides evidence (1) to support the claim of a relationship between GHG producing human activities to the effect of climate change and (2) highlight the possible risk of climate change on living systems as “reasons for concern” (IPCC, 2014). IPCC publishes reports with evidence from climate sciences that draw the link between global warming, its effects such as extreme weather and potential risks in long term climate change (IPCC, 2014). Such effects are recognised as a risk to current livelihoods and threats to future human existence. Although there are ongoing debates around whether climate change is related to human activities, an overwhelming majority of climate scientist agrees that “climate-warming trends over the past century are extremely likely due to human activities, and most of the leading scientific organizations worldwide have issued public statements endorsing this position” (NASA).

Information on physical climate change phenomena requires translation to inform policy. Assessment is a process that translates the “best-available scientific information” into terms that are “meaningful to policy-makers” (Scheraga *et al.*, 2003). “Policy-focused” or “policy-relevant” assessment is one of the bridges between climate science and policy (Scheraga *et al.*, 2003). “Policy-relevant” refers to an “iterative analytic process that engages both analysts and end-users to evaluate and interpret the interactions of dynamic physical, biological, and social systems and communicate useful insights in a timely fashion”. “Policy-focused” refers to research and assessment activities that are not directly “focused on answering specific questions being asked by policy makers” in the meantime but may be relevant for policy at a different point in time.

This is studied in an academic area through the development and use of Integrated Assessment Models of climate change (IAMs) at a global level, typically limited in geographical resolution. There are many variations of Integrated Assessment Models and the definition varies. Definitions include "model using multidisciplinary research knowledge", "model used in the integrated assessment of environmental science, technology and policy issues" and the combination of "natural sciences and economics in climate change issues, to evaluate policy options under climate change" (Wang *et al.*, 2017). These definitions reflect two broad kinds of models. The first broad kind of IAMs includes only natural sciences and economics concepts of cost-benefit economic models and employs simple assumptions to estimate the cost of mitigation and future climate damages. The second broad kind of IAMs includes other sub-models from other disciplines such as models of energy systems and land use models and their interactions. This kind of IAMs "estimate how GHG emissions from these systems might change in the future under different assumptions of future population and economic growth" (Carbon Brief, 2018). They are typically process-based.

An example is the use (UK CCC, 2008) of an IAM - Policy Analysis of Greenhouse Effect (PAGE) developed by Hope (2011), which models the impact of climate change and the cost of mitigation policies for a cost-benefit analysis. See Ackerman & Stanton (2014, p. 95) for a detailed review of IAMs.

1.4.5.2 From agreements between multiple countries to national target

The risk of climate change has been accepted as a basis for national policy in the UK (Parliament of the United Kingdom, 2008) and other counties evident in national commitment in legislation to reduce GHG emissions. The Paris Agreement sets out a target to keep global temperature rise below 2 degrees compared to the pre-industrial level (2oC target) and efforts to limit temperature rise to 1.5 degrees above pre-industrial level (UNFCCC, 2015).

The 2ºC target is often reiterated in organisations advocating for climate actions such as Science Based Targets (CDP, UN Global Compact and WRI, 2015) and Carbon Trust (Carbon Trust, 2018) as a basis for setting GHG emissions reduction targets. In the research literature, the 2oC target is often used as the starting point of exploration in studies such as cost-benefit analyses on initiatives to address climate change, emission reduction pathways (Cramer *et al.*, 2006) and the development of integrated assessment models (Wang *et al.*, 2017 for review; see Kanitkar, 2020) to understand the possible reduction based on possible initiatives through scenario testing. The global 2oC target and the related national GHG reduction targets are not without dispute and criticism (Randalls, 2010). However, as Gao et al. (2017) point out that, while the 2oC target is "more of a political consensus on the basis of scientific assessment than science itself, it provides a firm direction for action". In order to achieve the 2oC target, the concentration of greenhouse gas (GHG) emissions in the atmosphere have to be reduced.

Greenhouse gas and carbon emissions are sometimes used interchangeably. The Kyoto Protocol established a common standard that can be used for accounting the GHG from human activities between countries with a "basket of greenhouse gases" (UNFCCC, 2012) including Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF6).

The six gases have different levels of greenhouse effect. Nitrogen trifluoride (NF3) is sometimes included in the mix. The Global Warming Potential (GWP) of these gases is often used to combine the basket of gases as one carbon equivalent measure (CO2e) for ease of communication. Carbon dioxide (CO2) alone is often used in place of GHG emissions. The advantage is that CO2 can be estimated based on fuel used and its carbon content, whereas measurements or estimates from other gases can be difficult to obtain. The disadvantage is that actions aiming to lower CO2 may increase other types of GHG and emissions that are harmful to human health - for example, when a sliding scale related to CO2 emissions for car tax was introduced in 2001. Diesel vehicles typically have a lower CO2g/km rating than petrol vehicles but higher emissions of particulates and pollutants, which has a negative effect on local air quality. There are debates in the use of GWP as an indicator in terms of what is included and excluded, which are outside the scope of this study.

In broad terms, there are two ways to reduce GHG in the atmosphere. Firstly, GHG removal by means of absorbing GHG from the atmosphere - for example, by planting trees or using chemicals to absorb specific gases such as CO_2. Secondly, to reduce GHG emissions to the atmosphere.

The UK is legally committed to the reduction of GHG emissions through the Climate Change Act 2008 legislation, which sets a gross greenhouse gas GHG emissions reduction target of 80% from a baseline level in 1990; from 799 to 159.8 million tonnes net carbon dioxides equivalent (MtCO2e) emission. (Parliament of the United Kingdom, 2008) The UK total GHG emission in 2015 is reported as 495.7 million tonne net carbon dioxides equivalent. This represents a 38% reduction in Greenhouse gas emissions. In 2019, an amendment to Climate Change Act 2008 (2050 Target Amendment) Order 2019 set a target to reduce GHG emissions of 100% from the 1990 level as a **net zero** emission target.

“Net zero” also referred to as “carbon neutrality“ (EU, 2019). This is addressed by balancing out the total emission produced and removed from the atmosphere within a certain boundary - for example, an organisation such as a company or a country- or by “carbon offsetting” to “offset emissions made in one sector by reducing them somewhere else” (EU, 2019). It is acknowledged that there are sectors that are cost-prohibitive or not possible to reduce to zero emissions. However, there are carbon offsetting providers that enable companies to reduce emissions elsewhere.

The UK carbon budget sets out a limit on “the total amount of greenhouse gases the UK can emit over a 5-year period” (BEIS, 2016). The UK Committee on Climate Change (CCC) assess UK’s progress on meeting its carbon budget annually. There is a transition period until the carbon budget is set to the 2019 net zero target for the sixth carbon budget for the period 2033-2037.

The trend of the overall UK GHG emission reduction from 1990-2015 appears to be making good progress, and that UK emissions were 44% below 1990 levels in 2018. According to the CCC (2019), the first carbon budget (2008-2012) and the second carbon budget (2013-2017) were met and the UK is on track to meet the third carbon budget (2018-2022) but **not on track** to meet the fourth carbon budget (2023-2027) and fifth carbon budget (2033-2037) (UK CCC, 2019).

However, it is important to note that (1) there are limitations to some of the actions that had already contributed to the historical rate of reduction in certain sectors, such as retrofitting housing stock to improve housing insulation in that there is a limited amount of housing stock to be retrofitted (2) some sectors are limited in terms of cost of adaptation (3) certain sectors, in particular, **land-based transport for the movement of people have limited contribution to the overall trend of reduction over the period between 1990-2015**.

As part of monitoring towards the UK GHG emissions target, UK National statistics provide a territorial-based account of GHG emission estimates on an annual basis in accordance with the IPCC standards. The GHG emission estimates are modelled or calculated from emissions factors and the measured level of activity for each specific category of activities within sectors. The sectors include energy supply, business, transport, public, residential, agriculture, industrial process, land use change and waste management (Department for Business Energy & Strategy, 2016).
The transport sector is one of the main contributors of greenhouse gas (GHG) emissions and it is the largest contributor of UK GHG emissions in 2018 (Department for Transport, 2018).

There are two major reviews assessing transport, land use, economy and environment from the UK, the Stern report and Eddington transport study. Stern focuses on the economic impacts of climate change and suggests that emission reduction from the transport sector is challenging. The Eddington report focuses on the role of transport in supporting the economy. Docherty and Mackie, on a review of Eddington and Sterns report, suggested planning “can no longer be only about the use of land” but about “the spatial organisation of resources in pursuit of more carbon efficient development” (Docherty and Mackie, 2010).

1.4.6 GHG reduction in land-based transport for the movement of people

What is being done/can be done from spatial design/planning/policy perspectives?

This section first provides an overview of approaches to reduce GHG emission leading into the second part with further discussions in the assumptions and limitations of GHG emission reduction approaches related to land-based transport for the movement of people.

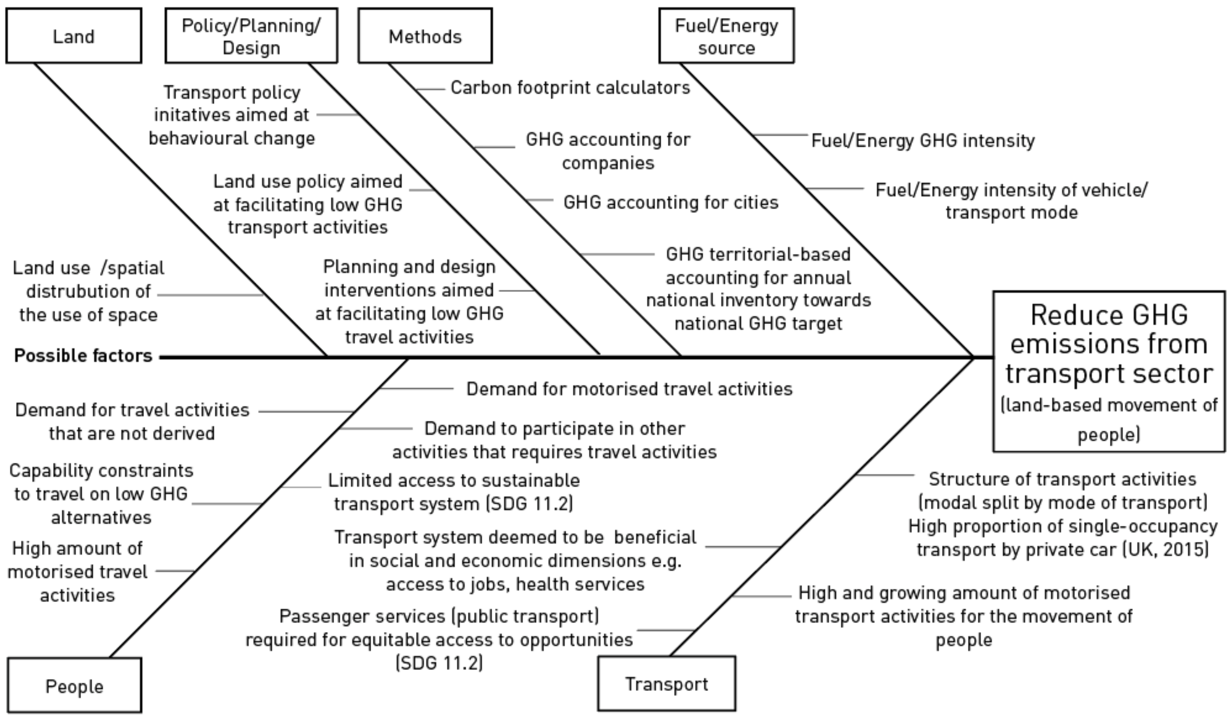

Figure 4 Fishbone diagram of GHG emissions from transport sector (Author's own)

1.4.6.1 Part 1: Overview of approaches to reduce GHG emission

The activity, structure, energy intensity and fuel (ASIF) framework (Schipper and Marie-Lilliu, 1999) was developed and commonly cited and adopted (Kutani, 2013; Li, Zhao and Brand, 2018) to estimate and understand transport energy use and emissions as an indicator that associates **transport activities and emissions** at a high level for both potential and actual situations. Activity, refers to the amount of transport activity which can be measured as vehicle distance travelled (e.g. vehicle kilometre travelled VKT) by mode or as a function of passenger distance travelled. Structure refers to the mode share of each mode. Intensity refers to the fuel intensity, which is the unit of energy consumption per vehicle distance travelled (energy unit/VKT). Fuel refers to the emission per unit of energy. This is typically referred to as emission conversion factors or emission factors (EF).

The Avoid-Shift-Improve (ASI) approach was developed to structure the general areas of diverse policy measures and interventions to reduce GHG emissions. The “avoid” aspect refers to trip reduction. The “shift” aspect refers to a modal shift from private motorised transport to public motorised transport or private non-motorised transport. The “improve” aspect refers to technological improvements that lead to emission reduction – for example, a more efficient engine and alternative fuel source (Dalkmann and Brannigan, 2007; Dhingra, 2011).

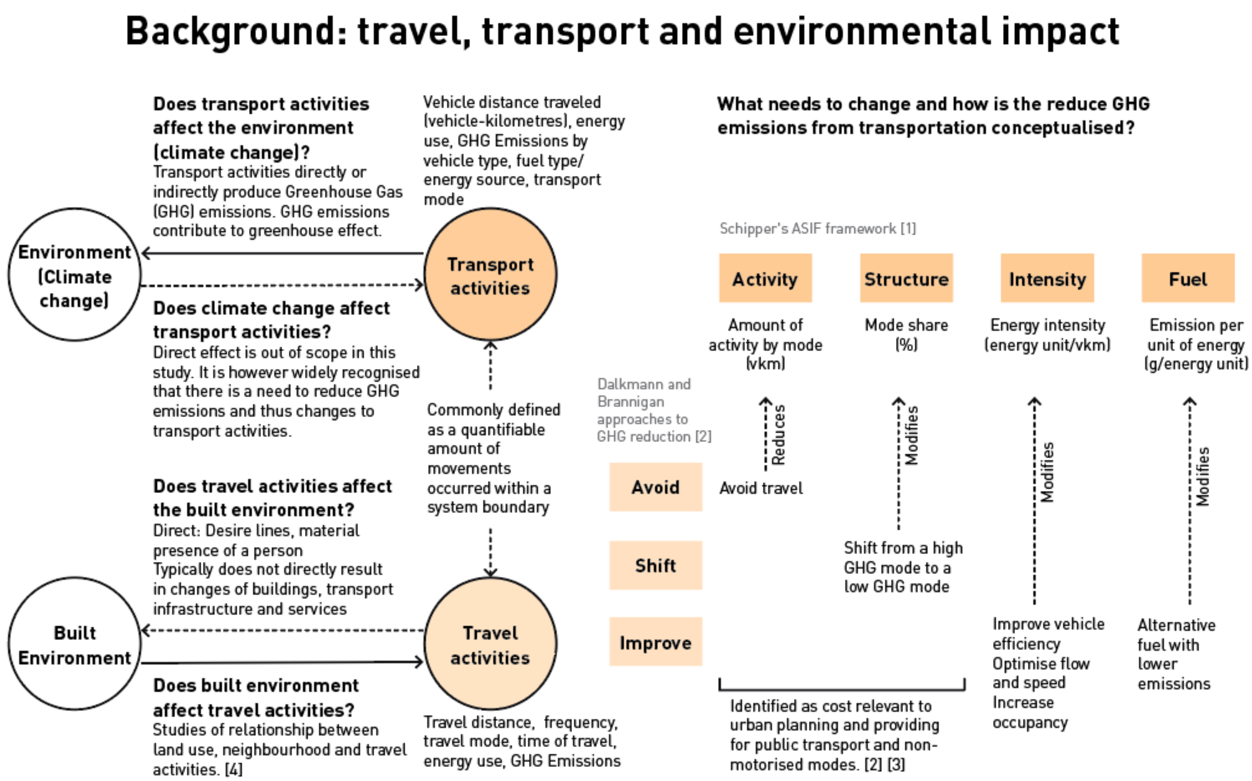

Figure 5 ASIF and ASI framework (Bongardt *et al.*, 2013) *to reduce environmental impact from transport*

A similar perspective highlights four kinds of areas: “substitution”, “modal shift”, “distance reduction” and “efficiency increase”. Substitution, modal shift and efficiency increase can be seen as synonymous to avoid, shift and improve respectively. Distance reduction can be seen as a sub-category to “avoid”. It is suggested that urban form can provide shorter trips, which reduces the travel distance and hence reduce emissions (Banister, 2008).

The association of the high-level assessment of GHG emissions from transport activities and the general areas of policy instruments towards a reduction in GHG emissions provides a framework that is relevant to disciplines that directly or indirectly influence the built environment towards facilitating the movement of people with lower GHG emissions (Tiwari, Cervero and Schipper, 2011; Bongardt *et al.*, 2013).

Indicator		Avoid	Shift	Improve
Activity	VKT or Number of Trips x Total passenger count x VKT	Reduce amount of transport activity e.g. Avoid trip (reduce amount of travel activity), distance reduction		
Structure	percentage of VKT by mode		Lower the percentage share of transport activities in high emissions transport modes e.g. Increase mode share in non-motorised modes and public transport	
Intensity	Unit of energy consumption per VKT or pkm			Improve vehicle efficiency Optimize flow and speed Increase occupancy
Fuel	Emissions per unit of energy consumed			Alternative fuel Fuel with lower emissions

Table 3. Adapted from "Relationship between ASI approach and ASIF framework" (Bongardt et al., 2013).

1.4.6.2 Part 2: assumptions and limitations of GHG emission reduction approaches

Reduction in GHG emissions in the transport sector towards climate change is not only about a reduction in GHG emissions. The following section discusses why this is and identifies associated dimensions of considerations.

As Brand et al. (2019) point out that it is well known that GHG emissions from transport are influenced not only by technical efficiency, modal share and the pollutant content of energy but also by "lifestyle choices" and "social-cultural factors". The interrelated concepts of **transport** and **travel** are useful for an integrative understanding of both a vehicle-based view of transport systems and a people-based view of travel activities and travel patterns.

Transport activities, by the adopted definition in this study, as previously stated in section 1.4.2 (pg34-35), are conducted by <u>motorised transport modes</u> and have associated direct or indirect GHG emissions as a result of energy consumption. **Transport activities** refer to the frequency (number of trips) and/or vehicle distance travelled in the context of GHG emissions-related studies (Schipper and Marie-Lilliu, 1999).

Travel activities refer to the movement of people that includes personal travel activities, which **contribute to the amount of** (through the use of private cars) or **make use of** (through the use of shared passenger transport services) transport activities, as well as the personal act of movement - for example, walking or cycling - without contribution to or making use of transport activities.

Direct or indirect GHG emissions is a commonly agreed way to understand GHG emissions from travel activities (World Resource Institute (WRI). C40 Cities Climate Leadership Group, 2014) and it is a different concept from the concept of embodied energy or embodied emissions commonly used for Life Cycle Analysis (LCA) in broad terms (see Čuček, Klemeš and Kravanja, 2012 for a description of LCA). There are similarities between the two, where both include indirect GHG emissions. However, there are differences in terms of the frame of analysis. The former focuses on the activity itself. In other words, if the activity were not conducted then the GHG emissions from the activity would not be produced (or at least not as a direct result of the activity). The latter is known to be applied to analyse GHG intensity of products, processes or services. In other words, if the product/processes/service of interest was not conducted, the GHG emissions from the products/processes/services would not be produced considering the whole life cycle of the products/processes/services.

What are the related approaches to reduce the amount of transport activities?
One way to reduce direct and indirect GHG emissions due to transport activities is to <u>reduce the amount of transport activities</u>. However, given that motorised transport activities currently support a large proportion of the total movements of people, a complete reduction of transport activities has an impact on other human activities in the social and economic dimension. Transport is said to be an “indispensable component of the economy and plays a major role in spatial relations between locations” (Rodrigue, Comtois and Slack, 2016). Although telecommunications enabled some form of shrinkage in the communication distance between people, transport is necessary for the movement of people and goods in physical space. Some of these movements of people in physical space are deemed to serve a social function, as transport provides “access to healthcare, welfare, and cultural or artistic events” (Rodrigue, Comtois and Slack, 2016).

Therefore, approaches to reduce transport activities in the context of GHG reduction tend to not aim at the complete eradication of transport activities but rather to reduce the amount of transport activity, for example, number of trips and travel distances with considerations in other dimensions.

In the UK, **motorised transport activities support a large proportion of the total movements of people**, or in other words, the amount of travel activities. This is evident in the high percentage mode share of motorised transport including private and public transport - 71% by the number of trips and 94% by travel distance in 2017 in the UK (Department for Transport, 2018) as well as the GHG emission in the UK from the transport sector for land-based passenger transport (BEIS, 2015).

The UK Department for Transport National Travel Survey 2018 indicates modal share in terms of average trip length with car use of 77%, train at 9%, bus at 4%, walking at 3% and cycling at 1% (Department for Transport, 2017). Modal share, when considered in terms of the number of trips, walking represents 27% while car trips are still dominant at 61%. The mode share by trip and average trip length for different modes of transport indicates there is a tendency to walk on shorter trips.

Motorised transport modes are required

If we <u>accept</u> that there is a large proportion of travel activities that <u>have to be supported</u> by motorised transport modes, what are the related approaches to reduce GHG emissions from the transport sector?

Technological change and alternative fuel transition from fossil fuel to electric, to reduce GHG emission per unit of energy consumed

In the UK, there are national policies and strategies related to the "improve" dimension through the use of alternative fuel. The UK government strategy of "Clean Growth" (UK Government. Department for Business Energy & Industrial Strategy, 2017) and "Road to Zero" (U. Department for Transport, 2018) aims towards a low carbon transition in transport with an emphasis on electric vehicles and hybrid vehicle. "Clean growth" aims to accelerate "the Shift to Low Carbon Transport" with an emphasis on low carbon fuel and "Road to Zero" aims to phase out solely fossil fuel-powered private cars with new vehicles to be "zero emission" by 2040. The most recent "Decarbonising Transport" (UK Department for Transport, 2020) includes the notions of a shift to "public transport" and "active transport" besides technological change.

"Zero emission" in this sense relates to local pollution and air quality in the wider environmental context of local emissions. A shift from fossil fuel vehicles to low local emissions fuel, such as electricity, can reduce local emissions and improve air quality as there are no tail-pipe emissions. However, particulate matter emissions from car tyres and brakes dust are still an issue (Timmers and Achten, 2016).

In the context of global climate change and GHG emissions, electric vehicles consume electric energy, which can produce GHG emissions at the point of energy generation, which in turn depends on the fuel mix for electricity generation. There had been a reduction of CO2 emissions from electricity generation in the UK through the switch from coal to natural gas and an increase in renewable energy sources, but it is still an emissions generation activity (BEIS, 2019). Electricity use in travel activities is commonly accounted as indirect emissions at certain scales of GHG accounting, for example, for companies reporting. Different scales of GHG system boundaries will be described and discuss in a later section 1.4..

Although there are arguments about the fuel mix for electricity generation, which electric vehicles still consume and therefore are indirectly related to fossil fuel-based electricity generation, Knobloch et al (2020) supported an argument for a shift from fossil fuel-based cars to electric cars and its contribution to GHG reduction target in their study (Knobloch *et al.*, 2020).

Individual behavioural change (1) to reduce travel activities or (2) to encourage a shift to travel modes that is deemed to be more sustainable, and thus aims to reduce transport activities (in the context where travel activities that has to be supported by motorised transport modes, a shift to public transport modes)

Another perspective is prominent in policy initiatives (such as "Smarter Choices programme in the UK (Cairns *et al.*, 2004b)) within the area of 'soft factor' interventions or soft transport policy measures that targets individual actions (Cairns *et al.*, 2004a). This includes workplace travel plans, school travel plans, personalised travel planning, public transport information and marketing, travel awareness campaigns, car clubs, car sharing, teleworking, teleconferencing and internet shopping (Cairns *et al.*, 2004b).

This type of transport policy measures is closely associated with both "avoid" and "shift" in the ASI framework. The former aims to reduce the amount of travel activities, for example through teleworking, and the latter aims to lower the percentage share of transport activities in high emissions transport modes.

For example, there has been a number of Volunteer Travel Behaviour Change (VTBC) programs that promote sustainable travel behaviour such as personalised travel planning initiatives or through ICT supported systems (Sunio and Schmöcker, 2017). While the approaches vary, the fundamental principle is to provide information to raise awareness of low carbon possibilities for businesses and individuals to make more environmentally-friendly decisions in their choice of travel activities.

This kind of policy measures, by definition, are aimed at changes in individual actions and thus related to a research area of behavioural change found in the literature. There are two large, broad areas in literature related to travel behaviour. The first broad area aims to **understand** travel behaviour. For example, discrete choice analysis of travel mode choice with an underlying economics foundation (Ben-Akiva and Bierlaire, 1999) and statistical models such as the use of Structural Equation Modelling was used to understand travel behaviour and values such as attitudes for deductive hypothesis testing (Daziano, 2015). The second broad area aims to **analyse or evaluate alternatives policies or initiatives** that are **posited** to change behaviour. For example, the use of Metropolitan Activity Relocation Simulator MARS (Pfaffenbichler, 2003) for a case study in Madrid, was used to test alternative policy scenarios including teleworking, densification, road pricing and public transport improvement (Alonso and Wang, 2017).

Studies in travel behaviour within a transport planning context are typically based on a theoretical basis in economics. This includes discrete choice analysis (McFadden, 1974), revealed preference (RP) and stated preference (SP) surveys (Ortúzar and Willumsen, 2011) and commonly reflected in the assumption of mode choice models in the second broad area where alternative scenarios are tested, both in transport modelling in planning practice (UK, 2014) and in research (Alonso and Wang, 2017). See section 2.2.2 for a literature review on "travel behaviour".

Barr and Prillwitz (Barr and Prillwitz, 2014) point out there is a need to "revisit the assumptions made concerning the role of individuals and their relationship to the underlying sociostructural and political challenges for reducing emissions from transport". It is argued that approaches focus on individual travel behaviour is limited and suggested an alternative perspective based on social practices. This perspective shifts the emphasis from changing **travel behaviour** to **travel activity** through an understanding of travel practices (Williams, 2018).

Travel activities on motorised modes can be substituted with non-motorised modes

If we do not accept that there is a large proportion of travel activities that have to be supported by motorised transport modes, what are the related approaches to reduce GHG emissions from the transport sector?

In order to not accept that there is a large proportion of travel activities that have to be supported by motorised transport modes, there are two broad kinds of approaches. These include:

(1) Efforts to shift travel activities conducted using motorised transport modes to non-motorised travel modes, assuming that the travel activities conducted using motorised transport modes can be substituted with non-motorised travel modes (for that reason, the argument is that travel activities do not have to be supported by motorised transport modes). The analytical frame in this approach typically assumes origins and destinations are fixed.

(2) Land developments with an associated analytical frame that has the potential to influence origins and destinations and the travel activities to traverse between the origins and destinations.

Shift to non-motorised travel modes

Targets a shift of travel activities from motorised to non-motorised travel modes

A known approach to this is to promote a shift to non-motorised travel modes such as walking and cycling. Walking and cycling are commonly regarded as the most sustainable form of travel (Marshall, 2001) with the additional public health benefit as a form of "active travel" (Handy *et al.*, 2002; Public Health England, 2016). The role of walking and cycling is recognised in UK "Road to Zero" (U. Department for Transport, 2018) strategy as part of policy action to support modal shift.

Research topics related to walking related to sustainability (Azmi and Karim, 2012) in a built environment-transport context is "walkable neighbourhood" and related indicators of "walkability" with various definitions (Forsyth, 2015), formulations (Frank *et al.*, 2005; Porta and Renne, 2005; Kuzmyak, Baber and Savory, 2006; Brown *et al.*, 2013) and studies based on indicators (Leslie *et al.*, 2007; Carr, Dunsiger and Marcus, 2011). For cycling, there are ongoing methodological developments such as the Propensity to Cycle tool (Lovelace *et al.*, 2017). The topics related to walking and cycling have a normative aspect directly related to disciplines that change or influence the built environment. There are published articles that suggest ways to achieve or justify "walkable city" including walking and cycling (Southworth, 2005), development of analytical methods for “walkability' (Badland *et al.*, 2013), developed as one of many scenarios in scenario analysis for future energy use in an urban context (Li, Zhao and Brand, 2018) and a combination of analysis and design with an aim to improve walking or cycling (Rakha and Reinhart, 2012) that are sometimes formulated as the development of a toolset (Saraf, Dogan and Samaranayake, 2018) for urban spatial planner and designers.

This promotion of shift to non-motorised travel modes assumes that travel activities conducted on motorised transport modes can be substituted by non-motorised modes. The following discusses why some travel activities cannot be substituted based on current situations.

Historically motorised transport and services reduced the travel time that is sometimes viewed as the reduction of the relative distance between physical space (Gunn, 2018). Historian Mumford suggests that “rapid public transportation, instead of reducing the time required for reaching the place of work, continued to increase the distance and the cost with no gain in time whatever” (Mumford, 1961, p. 430).

Along these lines of thought, there are related empirical studies on Travel Time Budgets. Marchetti used the concept of Travel Time Budget (Zahavi, 1974) first developed by Zahavi for transport analysis and Marchetti hypothesized an “invariant” constant travel time budget demonstrated by examples of the relationship between the area of Greece villages and walking speed and compared the city dimension of Berlin over time mapped to the prominent travel modes of the age (Marchetti, 1994).

Marchetti’s travel time budget assumes a constant fixed travel time budget for particular travel activities such as commuting to work that is the same across all countries. While there are studies that support this (Stopher, Ahmed and Liu, no date; Metz, 2012), such claim is contested and synthesis of empirical research suggests the concept of constant fixed travel time budget is limited at a local urban level (Joly, 2004). However, individual travel time expenditure shows patterns that are related to measurable characteristics, including “socioeconomic characteristics”, “attributes of activities at the destination” and the “characteristics of residential areas” (Mokhtarian and Chen, 2004).
Nonetheless, transport statistics in the UK (Department for Transport, 2018) have shown travel time, at least for the purpose of travel to work, has not been eliminated by a historical increase in speed from motorised transport and services. UK Office of National Statistics definition of “Travel To Work Area” includes the extent of labour markets defined using commuting flow data, similar to EU and OECD definition of “Functional Urban Area” (Dijkstra, Poelman and Veneri, 2019). The extent of TTWA from UK census has been reduced from 308 in 1991, 243 in 2001 and to 228 in 2011 census. This reduction of TTWA is attributed to an “increasing size of TTWAs, indicating longer commuting distances” (Bates, 2015).

Why some of the travel activities conducted using motorised transport modes **cannot be substituted** with non-motorised travel modes?

Although technically possible, it is unreasonable to consider that **all** travel activities can be conducted by non-motorised travel modes. Firstly, there can be a genuine need for motorised travel modes for people with physical restrictions in their everyday life as well as emergency services, including police, fire and health. Secondly, given that there is a general increase in travel distance over the past two decades in the UK, there is a limit for non-motorised modes to cover the same travel distance within the same travel time.

Although it may appear obvious that walking is typically slower than car travel over long distances, there are differences in magnitude when different travel modes are compared both in terms of fundamental limits of the travel mode itself and limitations in context. Studies often categorise travel modes in terms of slow modes, including walking and cycling, public transport and car. (Arentze and Timmermans, 2004; Highways, 2011; Teguh Aditjandra, 2013) The following illustrates these differences.

Huss et al. (2014) empirical study of speed by travel mode per trip sequence presented as a minimum to maximum range as well as average speed for all sequences provides an indication of the limitations of non-motorised modes. Within the study and the data presented, Huss et al. reported that walking has an average speed of 4.1 km/h between a range from 3.6 to 4.7 km/h, cycling has an average speed of 14.9 km/h between a range from 13.1 to 16.4 km/h, travel sequences by train has an average speed of 88.3 km/h between a range from 75.1 to 104 km/h, bus has an average speed of 31.3 km/h between a range from 24.1 to 33.7 km/h and car has an average speed of 41.7 km/h between a range from 35.6 to 53.9 km/h (Huss *et al.*, 2014). Given the set of indicative travel speed and an illustrative distance of 20km (for example, from Heaton Park to Manchester Airport, roughly North-South distance of Manchester district boundary), it would take approximately five hours to walk and one hour twenty minutes for cycling versus private cars in half an hour.

NM/M	Travel modes	Average speed (km/h)	Indicative time (minutes)	
			straight line	O-D in context
M	Car	41.7	29	24
M	Bus	31.3	38	101
M	Train	88.3	14	110 (*2)
NM (*1)	Cycle	14.9	81	82
NM	Walk	4.1	293	290

*Table 4. Indicative average speed (Huss et al., 2014) and calculated indicative time to traverse 20km by different travel modes (1) straight line distance and (2) A-B in context: between Heaton Park to Manchester Airport estimated from Google directions for a weekday at noon with considerations of transport network and services. Note *1: cycling taken as generally non-motorised although they can be motorised, UK regulations limits e-bike maximum speed to 25km/h (Great Britain EAPC, 2015) Note *2: multimodal with walking to and between stops/stations, bus and transfers.*

These figures are clearly indicative, and the actual context varies when the origin (O) and destinations (D) varies. Travel speed, time and distance are subject to the transport network, the effect of traffic. In particular, travel using public transport modes are limited to certain infrastructure, the availability of services and their routes. The illustrative values in this particular scenario show that travelling by car has a substantial advantage in terms of shorter travel time over other travel modes. For public transport such as bus and train, there is a drastic difference between the indicative value solely based on the average travel speed along a straight line distance and the indicative value in an illustrative context where schedules and routes are considered. It highlights the need to consider the level of service and routes when public transport is part of the consideration. The characteristics of transport/travel modes and the role of public transport in sustainable mobility will be discussed in a later section 1.6 pg62.

By focusing solely on a **change of travel mode** based on individual trips or aggregated trips, common in mode choice analysis and models (Sekhar, 2014), there is an underlying assumption that people have to get from one physical location to another. In other words, the **origins and destinations are seen as fixed and not part of possible change**. Given that there is a difference between the travel time to traverse physical space for motorised and non-motorised travel modes, where non-motorised modes are generally slower, an underlying assumption in people's **flexibility in travel time is required**.

Land development

Targets the spatial organisation that influence possible choice of origins and destinations

Reduction of travel distances is a broad notion that includes approaches related to sustainable mobility associated to **land development** (Banister, 2008) through spatial organisation "increasing densities and diversity through mixed use development" (Cervero, 2002), residential location, amenity location including the "availability of services and facilities", through types of urban development such as "car-free development", "public transport oriented development" (TOD) (Tiwari, Cervero and Schipper, 2011), and through design of buildings, space and route layouts (Rychlewski, 2016).

There are related research aims at **understanding built environment-travel patterns relationships** corresponding to the normative variations to increase density, diversity and considerations in residential, facilities and amenities location. The relationship between travel patterns and urban characteristics as density, diversity and design was conceptualised and studied by Cervero and Kockelman (1997) in their highly cited article. The study empirically tests the relationships as conceptualised against a background of new urbanism, transit-oriented development and traditional town planning as "ways of shaping travel demand" in a US context. Density metrics include intensity factor and accessibility index. Diversity metrics include land use mix, vertical mix and population within a quarter mile. Design metrics include walking quality factor, four-way intersections, quadrilaterals (urban block with four straight sides), sidewalk width and front/side parking (Cervero and Kockelman, 1997). Studies in **understanding built environment-travel patterns relationships** largely follow the same pattern where a set of metrics is defined to express certain urban characteristics deemed to be relevant to the topic that is statistically analysed against data on past travel patterns.

Residential location has long been a topic of economics-related study with a long history of development in location theories as part of economics geography (Pagliara, Preston and Simmonds, 2007) which operates at a level of a larger pattern, a well-known examples is Alonso's bid-rent theory (Alonso, 1964). Transport, in terms of one of the many notions of "accessibility" from Hansen has been associated to residential land use (Hansen, 1959) and it is widely adopted in urban simulation modelling (Cordera, 2018) especially when both land use and transport are considered (M Wegener, 2004). McFadden's development of discrete choice analysis on **residential location choice** (McFadden, 1978) The relationship between residential location and travel patterns has been supported by empirical studies (Naess, 2006). Conceptually residential location choice is seen as a higher-level structuring mechanism operating in a longer time frame (van Acker, van Wee and Witlox, 2010).

"Car-free development" and Transport oriented development (TOD) are types of urban development. Transport oriented development principles can be broad aims to reduce car dependency, increase public transport use, promote cycling. The spatial aspect of TOD is guided by the concept of catchment area varied by different travel modes and certain defined distances that are seen as reasonable or desirable. For example, a half-mile catchment area for rail stations is seen as a de facto standard (Guerra and Cervero, 2013) and the associated research had been to statistically test empirical ridership using station catchment area against other factors.

There are several research areas in terms of the design of building, space and route layouts towards the aim of sustainable mobility.

Development of analytical methods and tools for designer and planner (Gil, 2014, 2016; Lima *et al.*, 2017).

Within a frame of a normative aim to reduce GHG emissions while considering other economic and social dimensions, the role of land development in sustainable mobility is more than **reduction of travel distances** as Banister suggested (2008).

1.4.7 GHG emissions of transport-related activities: multiple units of analysis

Natural science continues to provide evidence to support the relationship between GHG producing human activities such as combustion of fossil fuel to the effect of climate change and have indicated the amount of GHG emissions to be reduced to keep global temperature rise at or below 2 degrees. The risk of climate change has been accepted as a basis for policy evident in UK and other counties' commitment in legislation to reduce GHG emissions. Natural science, however, has a limited role in understanding possible actions and decisions affecting human activities that could be taken to reduce GHG emissions.

In order to understand the situation with the inclusion of different human activities and their associated impact, there is a need to understand the different understandings of GHG emissions and how they are viewed in different contexts through various **constructs**.

In the context of this study, GHG emissions constructs are the various metrics and indicators that are commonly used in place of actual measure due to the fact that actual measurements are not feasible with the high cost and the varied types and amount of human activities involved. For example, a portable emission measurement system (PEMS) can be used to directly measure, empirically, emissions from vehicles in operation in real life (Liu *et al.*, 2010) but is costly to conduct at a large scale. An alternative to actual measurements is to measure by proxy. For example, the measurement of tree rings to "reconstruct past climate" (Jacoby and D'Arrigo, 1997), the appropriate use of these types of measurements is dependent on the purpose as they are restricted to a certain level of detail.

1.4.7.1 Measures within GHG constructs

The difference between "**measure**", "**estimated measure**" and "**indicative estimate**" is an important notion to clarify as "measure" is often used in literature to mean "estimated measure" or "indicative estimate". This study view "**measure**" as direct measurements of GHG emissions or derive from scientific proxy measures, "**estimated measure**" as estimates from empirical data of activities within a given time frame and GHG emissions per unit of activity, "**indicative estimate**" as an estimate of GHG emissions typically calculated from an estimated amount of activities and GHG emissions per unit of activity.

GHG emissions	Example of typical ways to derive a "measure" of GHG emissions	Context
Measure	Measurement using device, sensors or other instruments for a specific activity	Empirical measurement of GHG emissions for a specific activity
Estimated measure	**Measured** amount of activities within a given time frame x GHG emissions per unit of activity	GHG accounting Ex-post (after the fact)

		assessment
Indicative estimate	**Estimated** amount of activities x GHG emissions per unit of activity	GHG projection Ex-ante (before the fact) assessment

Definitions of different types of GHG emissions measures

GHG emissions per unit of activity are sometimes referred to as **emissions intensity metrics** or **emission factors** of an activity.

GHG emissions per unit of activity as **emissions intensity metrics** is the quantification of GHG emissions of a defined unit of activity over a specific time frame (GHG protocol, 2008). It is used to compare the emissions intensity between activities.

GHG emissions per unit of activity as **emission factors** are used to derive estimated measures and indicative estimates from activities. gCO2e per unit of electricity generated and gCO2e per vehicle kilometres are examples of GHG emissions per unit of activity. They are used to estimate GHG emissions from energy use and transport activities measured in vehicle distance (kilometres) travelled (VKT) for a given amount of activities.

Emissions intensity and **emission factors** are sometimes used interchangeably. This study uses these terms based on the difference in the **unit of activity**. As a basic example to illustrate the difference, when the focus is a comparison of **emission intensity** between multiple transport systems, the **emissions intensity** of per transport system is estimated from the total vehicle kilometres travelled and the corresponding **emission factor** assuming the fleet vehicles within each system are the same.

Transport system	Total vehicle kilometres travelled (km)	**Emission factor** (gCO2/km)	**Emission intensity** (gCO2/system)
System A	100	100	10000
System B	1000	200	200000

Table above illustrates the use of "emission factor" and "emission intensity" within this study through a basic example. The focus here is the emission intensity of each system (gCO2/system) using a corresponding emission factors (gCO2/km) and activities within each system as the total vehicle kilometres travelled (km). The emission factor can be seen as emission intensity if the focus is to determine the gCO2/km of different kinds of vehicles from a study.

The example given above uses a **constant emission factor** typically used for a simple representation of emission intensities. There are other representations of GHG emissions for specific purposes such as variable process-related emission factors and simulations. In a transport context, they are typically used to estimate road-based emissions where transport activities are simulated and variable emission factors from database record, such as the Handbook Emission Factors For Road Transport (HBEFA) that provides a more detail breakdown of emission factors by vehicle type and fuel type at different travel speed, are used.

Absolute and intensity

Another set of notions related to "**estimated measure**" and "**indicative estimate**" are "**absolute emissions**" and "**emissions intensity**". "**Absolute emissions**" is the amount of GHG released to the atmosphere within a defined system boundary – political or geographical area, activities included and excluded, and time period.

"**Emissions intensity**" refers to the GHG emissions relative to a unit of activity. There are at least two kinds of "unit of activity" that can be identified.

The first kind of unit is standard units derived from metrology for example kilometres used as a measure of activity in CO2 emissions per kilometres of different kind of vehicles (Ryan, Ferreira and Convery, 2009).

The second kind of unit derives from other forms of quantifications, usually from economics. For example, Gross Domestic Product (GDP) is an indicator of the economic output of a country. In transportation, a unit of passenger-distance, often as passenger-kilometres (pkm) is used to represent the total movement of passengers for passenger transport services. Passenger-kilometres (pkm) is defined as the transport of one passenger over one kilometre.

Absolute emissions and **emissions intensity** are often associated with emissions targets. **Absolute reduction targets** specify GHG reduction by its amount relative to a historical baseline. The UK national emission reduction target is an absolute target. **Intensity reduction targets** are GHG emissions reduction relative to economic output. An intensity-based emissions target thus takes account of the levels of economic activity. A typical example of an intensity target is GHG emissions and Gross Domestic Product (gCO2/GDP). (Baumert, 2016)

	Example of unit
Absolute emissions	gCO2
Emissions intensity 1	gCO2/km
Emissions intensity 2	gCO2/GDP or gCO2/pkm

1.4.7.2 Overview of GHG constructs for estimated measure in different scales/unit of analysis

In order to gain an understanding of GHG emissions estimates with different definitions of the unit of activity, this section aims to provide an overview of the constructs for GHG emissions estimate that can be found in the literature with a specific focus on the **scales** in which it is applicable.

The “**scales**” here are referred to as a frame of estimation in relation to the **unit of activity**. The scales identified here include **national**, **city and organisation** as composites of other units of activities, including industrial processes, transport, goods and services in the forms of GHG accounts. In addition, GHG constructs outside the scope of GHG accounts in the scale of **household** and **individual** are described.

The constructs include GHG accounts and embedded constructs of GHG emissions, such as carbon footprint. Although GHG accounts are seen as constructs that are inherently value-embedded due to the need to understand the GHG producing activities involved in a country, city or organisation as opposed to pure factual measurement of atmospheric GHG emissions in this study, as Ascui and Lovell point out, that GHG accounts are an “essential enabler of several of society’s key responses to the problem of climate change, including national emission limitation commitments, corporate climate change performance targets and carbon markets” (Ascui and Lovell, 2011).

Each identified “scale” starts with a general description of the related GHG constructs and further descriptions are limited to the constructs relevant to urban transportation.

1.4.7.2.1 National GHG accounts

GHG accounting methods such as the territorial-based accounting can be found in academic and grey literature to assist in monitoring the GHG emissions emitted from different sources of economic activities on an annual basis towards national emissions target.

At a national level, there are three main types of constructs used for accounting GHG emissions.
1) Territorial-based account – includes GHG emissions within a geographical political boundary
2) Residential-based / production-based account – includes GHG emissions from residents within a geographical political boundary
3) Consumption-based account – includes GHG emissions from the consumption activities within a geographical political boundary
The UK territorial-based account is produced in accordance to IPCC guidelines and is agreed amongst most countries. The territorial-based account is commonly contested in academic literature with the alternative of consumption-based account.

1.4.7.2.2 Cities and organisations

Beyond the national accounts, GHG Protocol is an international reporting standard GHG emissions developed by the World Resource Institute (WRI) and other related international organisations. The GHG Protocol provides guidance in reporting GHG emissions for cities and organisations, does not prescribe the methodology for the calculation but recommends calculation methods. The standard is structured around three scopes with variations in what is included and excluded in different contexts.

Scope 1: Direct GHG emissions
Scope 2: Energy indirect GHG emissions

Scope 3: Other indirect GHG emissions

GHG Protocol for cities (community-scale GHG inventories) (World Resource Institute (WRI). C40 Cities Climate Leadership Group, 2014)

The guidelines for transportation in a city scale include two levels of reporting 1) BASIC and 2) BASIC+:

- BASIC - "Cities shall report all GHG emissions from combustion of fuels in transportation occurring within the city boundary in scope 1, and GHG emissions from grid-supplied electricity used for transportation within the city boundary for transportation in scope 2"

- BASIC+ - "Cities shall report all BASIC sources and scope 3 GHG emissions associated with transboundary transportation"

Specific guidelines were given in terms of system boundaries for measurements as travel modes can either be wholly contained within city boundary or cross city boundaries into neighbouring areas.

Type 1: “Trips that originate in the city and terminate outside the city”
Type 2: “Trips that originate outside the city and terminate in the city”
Type 3: “Regional transit with an intermediate stop within the city”
Type 4: “Trips that pass through the city, with both origin and destination outside the city”

Given these possible trips types in GHG Protocol for cities, scope 1 and scope 2 are territorial-based and scope 3 accounts for the out of city portion of the trips stops at the city.

Scope 1: includes all GHG emissions from the transport of people and freight occurring within the city boundary.
Scope 2: includes all GHG emissions from the generation of grid supplied electricity used for electric-powered vehicles. Amount of electricity used should be assessed at the point of consumption within the city boundary.
Scope 3: includes out-of-city portion of all transboundary GHG emissions from trips types 1, 2, 3. Large regional transit hub outside boundary but serving the city should be counted.

GHG Protocol for cities does not prescribe a specific method for calculating road-based emissions due to variations in data availability, existing transportation models, and inventory purposes. The document describes four common methods for road-based emissions include:

1. Fuel sales method – using the amount of fuel as a proxy for fuel consumption
2. Induced activity method - relies on models or surveys to assess the number and length of all on-road trips. uses VKT, vehicle fuel intensity and fuel emission factors

3. Geographic or territorial method - quantifies emissions from transportation activity occurring solely within city boundaries, regardless of the trip's origin or destination
4. Resident activity method - emissions from transportation activity on city residents only.

1.4.7.2.3 GHG accounts for organisations (WBCSD and WRI, 2012)

The UK Companies Act 2006 (Strategic and Directors' Reports) Regulations 2013 states that "quoted companies are required to report their annual greenhouse gas (GHG) emissions in their directors' report".

Scope 1 includes "Transportation of materials, products, waste, and employees. These emissions result from the combustion of fuels in company owned/controlled mobile combustion sources (e.g., trucks, trains, ships, airplanes, buses, and cars)" (WBCSD and WRI, 2012)
Scope 2 includes "Applicable if the operation of or equipment owned or controlled by the company consumes purchased electricity. " (WBCSD and WRI, 2012)
Scope 3 includes "Other indirect GHG emissions: Transport-related activities • Transportation of purchased materials or goods • Transportation of purchased fuels • Employee business travel • Employees commuting to and from work • Transportation of sold products • Transportation of waste" (WBCSD and WRI, 2012)

1.5 Computational analytical construct

This research is motivated by an interest in computational spatial analytical and simulation models of urban systems. It places particular attention to the relationships between urban environment and the potential travel activities and the extent in which they can be used to analyse changes in the built environment that "encompasses patterns of human activity within the physical environment" (Handy *et al.*, 2002) before the event (ex-ante) and to anticipate the possible implications of future spatial configuration/arrangement/structure towards urban sustainability, in particular through sustainable accessibility (Bertolini, le Clercq and Kapoen, 2005; Curtis and Scheurer, 2010) for ex-ante spatial design (Dijst, de Jong and van Eck, 2002) and planning evaluation (Khakee, 1998).

1.5.1 The need for computational analytical construct

The special issue on "evidence-informed and analytical methods in urban design" (Karimi, 2012) from the urban design international journal highlighted one of the problems in urban design. More specifically, "layers upon layers of data, from building and physical conditions to social and economic issues" are collected, "beautifully presented" but they are disconnected from the act of design that is **solely** based on the team's "assumptions and experiences". Karimi points out the need for a methodology to help "analyse the data and understand its implications for design" and the need for its integration into a design process.

In order to understand design processes related to architecture and research in architecture, it is useful to understand different types of research orientations regarding design methodologies in architecture and current trends in terms of analytical methods.

Franz (1994) identifies three broad types of research orientations related to architectural design processes (1) technically oriented research (2) conceptually oriented research and (3) philosophically oriented research.

The recent growth in building/city information modelling (BIM/CIM) and parametric design evident in the Cumulative Index about publications in Computer Aided Architectural Design (Cummincad, 1998) and related academic conferences has greatly increased the knowledge on the "technically oriented research". Building/city information modelling and parametric design have frames of reference of management of information and generation of geometries, respectively. The way in which the spatial/geometrical outcomes of a design process are analysed and interpreted remains an area related to but beyond technically oriented research especially when the pre-supposed values are under question and the desired outcomes are societal related. They are more aligned to what Franz identified as "conceptually oriented research" which includes but is not limited to "a psychological frame of reference" (environment-person) and "a person-environment frame of reference" with awareness of social and environmental issues as well as "development of methods and models that could support client/user participation in the design process". "Conceptually oriented research" contains elements that are investigated in research contexts outside architecture and urban design. The characteristic in "conceptually oriented research" is the consideration of the relationships between people as the target users, and environment as the subject of design as well as the people involvement in the design process. The various conceptualisations of the relationship between people and the environment are discussed in a later section 3.2.

1.5.2 The role of computational spatial analytical frameworks

It is acknowledged that intuition and creativity are important inputs in design. However, as mentioned earlier in 1.5.1 pg59, there are calls for, some if not all, design processes to be "informed by more rigorous and objective methods" (Karimi, 2012).

In the context of "computational analysis", although "computational" is "technically oriented", "analysis" does not necessarily need to be "technically oriented". There is research and development of computational analytical methodologies that is aligned to "conceptually oriented research" and aid the investigations of relationships between people and the environment. There are theories, models and models as "embodiment of theory" (Batty, 1992) related to the analysis of urban areas in broad terms, including land use models, transport models, environment models, economic models and geographic information systems (GIS) and urban simulations that are used for analytical purposes. These are relevant for the role of architecture and urban design in physical spatial transformation as well as the role of spatial design, policy and planning of **urban development** in a wider context of **urban transitions** and **transformations**.

What is currently being done in design related to urban movements?

In an architectural urban design context, there is a common emphasis on personal modes of travel, typically walking, cycling and private vehicles. There is a typical focus on walking as a travel mode through the **configuration of street network** and an emphasis on the quality of space between buildings. There are examples when a combination of travel modes is considered with an emphasis on the differences in permeability for vehicles and other personal travel modes such as walking and cycling. For example, “Superblocks” in Barcelona developed by BCNecologia, “fused grid” in Calgary, Canada and the most recent proposal of the “Toyota Woven City” - a “prototype city of the future” proposed by BIG architects and Toyota with a proposed development in Susono, Shizuoka, Japan near Mount Fuji. The underlying principles for “filtered permeability” (Melia, 2012) can be seen in these types of projects as a way to organise different types of movements in an urban situation.

One known practice can be seen from design justified by a **set of guidelines** in the form of normative statements. In a wider strategic planning context, there is Planning Policy Guidance (PPG13 transport) in UK planning policy, which is replaced by the National Planning Policy Framework (NPPF) 9 promoting sustainable transport in 2012. The policy framework provides a set of normative statements towards goals that are deemed to be desirable by policy makers.

Another known practice can be seen from the design of **guiding principles** in strategic planning approaches. At a regional level, for example, the Greater Manchester Spatial Framework (GMSF) developed by the Greater Manchester Combined Authority (GMCA) in 2019 establishes a set of normative statements towards goals for the region. Another known practice can be seen from design informed by a set of **design principles** – for or example, design principles based on the concept of Transit-Oriented Development (TOD). There are TOD standards developed by Institute for Transportation and Development Policy in 2014.

Another known practice in the design of future urban plans is **to follow or imitate an existing situation that is seen to result in desirable outcomes**. For example, Barcelona “superblocks” can be seen as a system that allows others to follow or to imitate in order to achieve a similar result.

It is worth noting that while precedents of past projects or a set of principles are sometimes referred to as “model”. The term “model” refers to "something that a copy can be based on because it is an extremely good example of its type" (Cambridge dictionary online) they are different from the kind of “models” referred to in this study as **computational spatial analytical and simulation models**.

1.5.2.1 Computational analysis in design and decision-making process

What are the kinds of computational analysis that is being applied to design and decision-making process related to the topic of urban movements?

The eventual outcomes of spatial planning and policy action can result in (1) no changes in the physical material space but changes in other aspects such as functional and organisation or (2) changes in physical material space. (Chadwick, 1978, p. 98)

Spatial description of urban situations is an important aspect to understand proposed changes in physical material space whether or not the urban situation is planned following a rational comprehensive approach from a conventional point of view or an interpretation of multiple possible future scenarios as conceivable outcomes of strategic plans or from the point of view of more recent urban planning approaches including transactive, advocacy, bargaining and communicative approaches (see Susan, Fainstein and James, 2015 for an overview of planning theories).

In general, most architectural computational analysis for spatial design and planning has an emphasis on geospatial or geometrical inputs that analyses physical spatial phenomenon. An example of this is the daylight analysis for sky view factor (Al-Sudani, Hussein and Sharples, 2017), analysis of the configuration of building mass and space in-between to reduce urban heat island effect (UHI) (Yang, Lau and Qian, 2011). There are examples, though limited within architecture, of computational analysis that takes a spatial description of an urban situation usually as an outcome of design and attempts to produce insights related to socio-spatial phenomena such as urban transport and travel activities. (see section 2.3 state-of-the-art review pg89)

On the other hand, different kinds of computational analysis and its underlying analytical frameworks **have long been researched, developed and evolved to support decision-making processes at an urban strategic level**. In particular, on the research side associated to the development of urban models and simulation of urban systems (Batty, 2008a) and as a separate but sometimes overlapping branch of research on decision/planning support systems (DSS/PSS) interfaces between decision maker, computational urban models and its associate analytical methods.

1.6 Wider problems definition

1.6.1 The problem of passenger transport shared by multiple passengers in the context of GHG reduction

Climate change is widely recognised as a pressing issue and sustainability is a widely acknowledged common goal. The development of the urban environment, including considerations in land development and transport systems, has an important role in sustainable development (SDG11). Land development and transport systems facilitate and constrain the way in which travel activities can be performed. There is, therefore, a need to understand how the physical and functional aspects relate to possible travel activities, some of which can be seen as more environmentally sustainable. However, as Barr and Prillwitz (2014) point out the links between travel mode choice at the individual and group scale and environment at a global scale is complex and sometimes contested.

It is widely acknowledged that non-motorized travel modes, such as walking and cycling, are environmentally sustainable compared to motorized travel modes (Marshall, 2001) and public transport. In addition to non-motorized travel modes are “generally agreed to be sustainable alternatives to car travel” (Redman *et al.*, 2013).

Although passenger transport modes are seen as important for sustainable transport and mobility, whether a passenger service can be seen as a sustainable mode of travel is context dependant. Research typically assumes that public transport as a form of passenger transport is more sustainable especially when the frame of reference focuses on individual behaviour (Barr and Prillwitz, 2012) travel practices (Cass and Faulconbridge, 2015) or from a demand management perspective (Dalkmann and Brannigan, 2007; GIZ, 2011). From a service provider frame of reference on the supply side, “high occupancy rates are an important requirement for the **economic and environmental viability** of public transport” (Sims *et al.*, 2011).

Another dimension to this problem is the **competition between different travel modes** within a contextual aim towards a reduction in Greenhouse Gas (GHG) emissions. From a city perspective, it is clear that a shift away from personal private motorised travel mode is the ideal. At the same time, a shift from non-motorised modes or passenger modes to private motorised travel mode – an additional vehicle thus additional energy use leading to indirect or direct GHG emissions - would have increased the GHG emissions at the city level. Passenger transport in terms of conventional fixed route scheduled public transport are legally required to operate in the UK even when there are no passengers on board. A **shift between (to and from) non-motorised travel mode and public transport has, therefore, no direct effect towards a reduction in GHG emissions at a city level.**

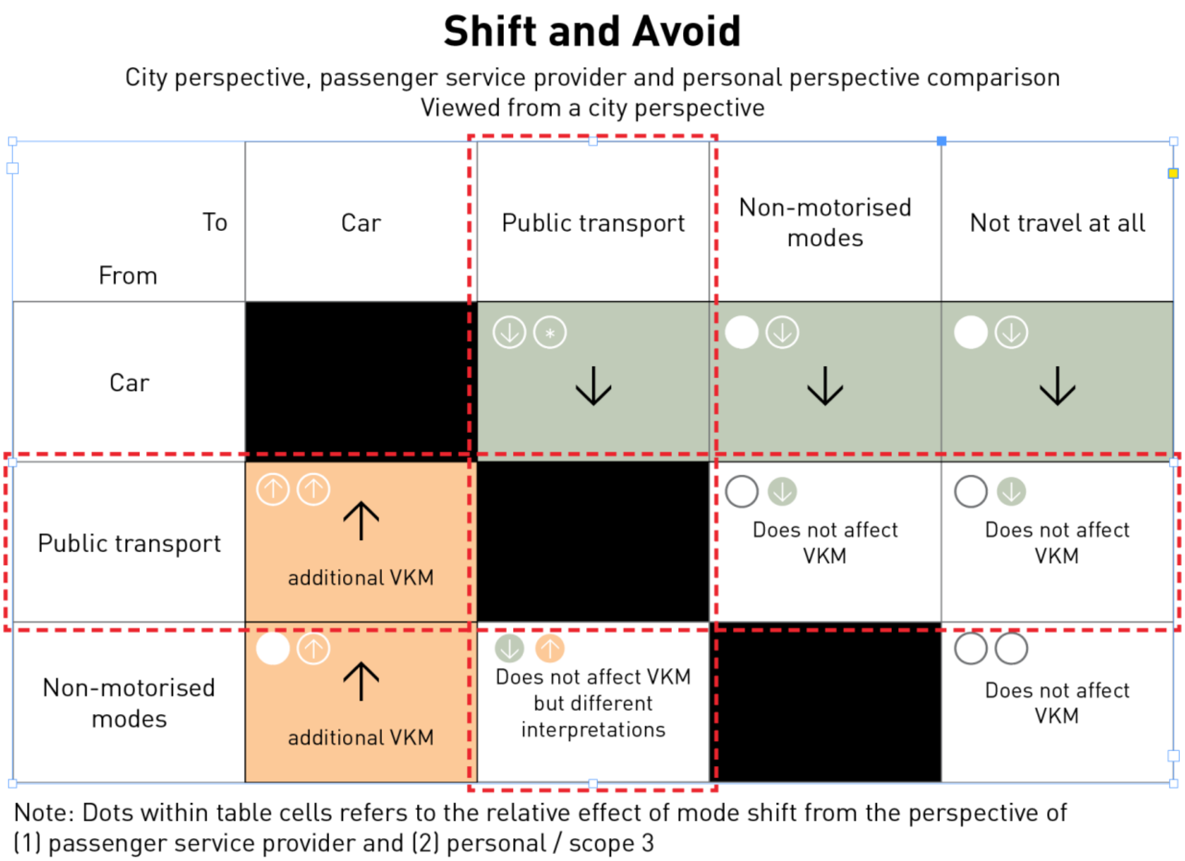

Figure 6 From a personal perspective, shifting from public transport to walking can lower personal GHG reduction but has no effect at the system level. Equally shifting between public transport and walking has no effect. The only way in which mode shift work is from car to public transport or non-motorised modes.

Passenger service providers are important when considering multi-modal transport. The existence and ability to sustain the passenger service relies on economic viability (Sims *et al.*, 2011). There are situations where the public transport coverage is sought from a city perspective on low ridership routes, the UK government or local authorities subsidise these routes when running these non-profit routes are deemed to be beneficial (GMCA, 2019). A considerable amount of research in Public Private Partnership associated to transport planning. In the UK, outside London, public transport such as buses and trams are currently operated by private operators, for historical reasons. The recent development in transportation for public use sees a combination of services and information technology with a number of private companies in operation, for example, Uber and Lyft and are under pressure for profit. Other known alterative passenger services that have long been proposed and implemented include demand responsive transport, microtransit and personal rapid transit. This is coupled with technological progress in the development of autonomous vehicles where the potentials of passenger services using a fleet of autonomous vehicles have been studied.

1.6.1.1 What about passenger service planning?
Planning of passenger service is an interest of **service planning** (transport/transit). Service planning involves network design and route design. Problems in network and route design have been formulated to find optimization or satisficing solutions towards defined objectives (Kepaptsoglou and Karlaftis, 2009). For example, Transit Route Network Design Problem (TRNDP). In the context of sustainability, the problem is solely aimed at optimising service design parameters such as route and frequency towards objectives commonly considered in TRNDP with the inclusion of sustainability-oriented objectives such as environmental impact (Pternea *et al.*, 2015).

1.6.1.2 What about studies in passenger service?
There are existing studies on the **use of existing** public transport services expressed as ridership or patronage from available data (see Taylor, Fink and Org, 2003 for an overview). These kinds of studies are designed to describe and explain **external factors** and **internal factors** that affect public transport ridership in an aggregated level. An example of external factors is socio-economic factors such as employment levels of regions to the patronage of public transport. "**Spatial factors**" or "**urban form**" is another example of an **external factor**, which in this research context, is a quantification of characteristics of a defined spatial unit. For example, Cervero (1993) study in the Ridership Impacts of Transit-Focused Development in California characterized space as "land-use mix" indicator, "proximity" to rail stations and "density" where the rail modal share amongst other travel modes are correlated. The study finds close proximity to rail stations and higher densities has the biggest influence on ridership while levels of mixed use or quality of walking environment have a negligible influence. Similarly in a regional context, a study to relate energy use and urban form, urban form is viewed in terms of "density", "size of urban area" and "mixed land uses" (Banister, Watson and Wood, 1997). **Internal factors** include pricing, service quality e.g. reliability and service quantity e.g. service coverage and service frequency.

While empirical study provides important descriptive and causal insight in public transport ridership for a specific context useful for the management of existing systems, the "generalizability of studies examining a small number of systems is limited" (Taylor, Fink and Org, 2003). Thus insight cannot be directly applied to a spatial or service design and planning perspective for a new situation in a different context.

1.6.1.3 What about studies in transport planning and related research?
An alternative angle, from a transport planning point of view, the occupancy rate of passenger transport is related to transport demand - the number of people using a passenger transport service where the occupancy rate as a metric can be estimated through the use of model and simulation. The core assumption is that **demand for transport is derived**, while there are acknowledged exceptions, typically "people travel in order to satisfy a need (work, leisure, health) undertaking an **activity** at particular **locations**" and "in order to understand the demand for transport, we must understand the way in which these **activities are distributed over space**" (Ortúzar and Willumsen, 2011).

The general view of **activities** over **space** and **transport demand** has been conceptualised as the interaction between a transportation system including transport infrastructure and services and an activity system including the spatial distribution of **land use**, **socio demographic** and **economic activity** associated to a unit of space (Manheim, 1979; McNally, 2000b) for transportation system analysis.
The **activity-based approaches** that emerged in the 1980s provide a view that is more akin to travel demand "as a derived demand that arose from people's desire to pursue activities in time and space" (Weiner, 2016). **Activity-based approaches** open up new opportunities in scenario testing for a wider range of policy questions (Arentze and Timmermans, 2000; Shabanpour *et al.*, 2018).

Prior to the development of activity-based approaches, typical policy questions related to transportation have been about the question of the **supply** of large-scale infrastructure, such as the expansion of highway since the 1960s (McNally, 2000b). This role of transport modelling persists, for example, in the use of transport model for transport project appraisals (UK Department for Transport, 2013). There has been an increase in efforts towards non-material aspects in transportation such as road pricing and ride sharing, with a general aim to influence **demand**. There has been an increase in research development in activity-based approaches for travel demand modelling (Bhat and Koppelman, 2003).

Transport-integrated city design

Land use or at a more detail spatial level as **location of activity participation** and **transport infrastructure** has been recognised as part of a spatial description of a city and is of overlapping interest in **spatial planning, urban planning, transport service planning and transport planning**. At the same time, urban spatial planning, urban planning, transport service planning and transport planning are separate fields that are relevant in the **shaping** of the built environment with different but sometimes overlapping concerns and emphasis.

An **integrated view of urban and transport planning** is recognised in transport policy (Hickman and Banister, 2007) and evident in a long history of urban system simulation modelling activities as Land Use Transport Integrated models (LUTI) (M Wegener, 2004; Acheampong and Silva, 2015) towards **analysis of planning and policy scenarios** (Waddell, 2000) and their potential to analyse the impact of infrastructures and spatial development to address the objectives of sustainability (Kii *et al.*, 2016).

Even though there is a general trend towards micro scale, fine grained considerations in the model representation of people and space in a LUTI context (Iacono, Levinson and El-Geneidy, 2008), the translation from strategic spatial plan to spatial design has remained at a geographical scale and research programme with associated research traditions that are **not directly applicable in city design**.

An alternative viewpoint from literature with an urban spatial design orientation draws heavily upon analytical metrics of urban characteristics - for example, space syntax metrics, density metrics, diversity metrics, design metrics. In normative applications to support design decisions, they have an ability to support design decisions at a pattern level – the interpretations of metrics in a specific location suggest certain likely outcomes at a pattern level, which are supported by research using the metrics as measures. This approach is limited and lacks the input sensitivity towards an understanding of the current trends in the innovations in passenger services and the shift from physical travel to telecommunication.

Development of analytical framework for "people-based accessibility" (Iacono, Levinson and El-Geneidy, 2008), however, offers opportunities for the integration of **urban spatial design** and **transport service planning** considerations as well as **personal and circumstances in joint travel**. It is possible to locate previous studies and theoretical approaches that are compatible with spatial design as the spatial arrangement of locations and transport network; transport service planning that includes an emphasis on time – e.g. level of services including the decision on frequency and intervals.

1.6.1.4 The limitations in the most relevant computational analytical constructs

The **activity-based approach** (see 2.2.3.2) which has been actively developed towards travel demand models in recent years (TASHA, ALBATROSS) and **person-based accessibility** has the same theoretical root in Hagerstrand's time geography (McNally, 2000a; Ellegård and Svedin, 2012) and operational root in Lenntorp's analytical framework as part of his PhD thesis (Lenntorp, 1976).

Although an **activity-based approach** has been developed towards predictive demand modelling, there has been **a time when activity-based approach is not aimed towards predictive travel demand modelling** but studies with an emphasis on understanding the **constraints from the urban environment on person-based accessibility towards spatial planning and service planning**. This is framed around the interaction between two types of possible changes that can be made towards desirable goals in the wider context – change in the urban environment and change in citizens' activity and associated schedule and location.

Lenntorp's (1976, 1978) developed Hagerstrand's classical time geography **theoretical constructs** as an **analytical framework** named Program Evaluating the Set of Alternative Sample Paths (**PESASP**) to study the constraining effect of the urban environment. This included the transport network and locations of activity participation against individual daily schedules. The analytical framework is demonstrated in a case study to investigate travel possibilities in the city of Karlstad with an aim to understand public transport from the citizen's point of view (Lenntorp, 1978). The second novel development along the same perspective, to understand spatial and service planning, has been Dijst's Model of Action in Time Intervals and Clusters (**MASTIC**) (Dijst, 1995). It has subsequently been demonstrated in a case study in Zoetermeer to understand the opportunities for citizens to make use of alternative travel modes, other than the car, given the activity programme, including time allocated in a day for work commitments, times of appointments and other participation of activities that required travelling of desire. (Dijst, de Jong and van Eck, 2002) The percentage of activity programmes that could be substituted from cars to other travel modes was reported as the potential for travel mode change. The result from the analytical process also reveals other insights. For example, the potential shift from car to other modes is limited due to extensive trip time when testing substitution of locations for activity participation. Similar to PESASP, MASTIC also facilitates the analysis of the number of different ways an activity programme can be conducted within a given urban environment. This has been conceptualised as an indicator of "**freedom of choice**". The higher the freedom of choice means there are more flexibility for citizen to alter their daily schedules e.g. different sequence of activities or location.

There are **developments of analytical model** both in the **underlying construct**, **model and methods** along a similar line of thought but different in their aims and goals. The following section briefly describes the branches of developments.

One early example following a similar underlying rationale but towards a different aim is Combinatorial Algorithm for Rescheduling Lists and Activities (**CARLA**) (Clarke and Dix, 1980). It was developed as part of a research project on "Understanding Travel Behaviour" at the Transport Studies Unit in Oxford. Although the underlying basis is conceptually similar to PESASP and MASTIC, the emphasis in CARLA is **activity scheduling** and "the spatial component of the time-geographic framework is relaxed in favour of analysing the **ability to carry out different activities at particular time points within observed activity sequences**" (Pickup and Town, 1981). Following the same line, Jones (1983) development of the Household Activity Travel Simulator (HATS) marks the beginning of a "human activity approach" (Fox, 1995) to analysis of travel behavior, which eventually lead to activity-based approaches in transport modelling and travel analysis. HATS was developed within a game-scenario based research approach to test participant's responses to hypothetical changes - proposed change in the environment affecting participant's schedule in space and time.
Another major branch can be identified, which is characterised by the algorithmic **generation of activity patterns** motivated by previous studies in understanding possible responses and implications of change through activity schedules. Research in this area to generate activity patterns typically aims towards prediction-oriented travel demand modelling.

For example, Prism-Constrained Activity-Travel Simulator (PCATS) (Kitamura and Fujii, 1998) that contains a utility-based formulation of choice within space-time prism from classical time geography. PCATS produces trip demand and has been shown to couple with a dynamic network simulator, DEBNetS for prediction-oriented travel demand modelling (Kitamura and Kuwahara, 2005).

Another example, A Learning Based Transportation Oriented Simulation System (ALBATROSS) (Arentze and Timmermans, 2000) has been developed a computational process model instead of a utility-based formulation of choice. ALBATROSS can be used as part of a larger travel demand simulation system of Forecasting Evolutionary Activity-Travel of Household and their Environmental Repercussion (FEATHERS) (Bellemans *et al.*, 2010).

There are further developments in the spatial methods associated to the time geography from **Geographic Information Science**. The advances in Geographic Information Science is related to the notion of urban accessibility through the further development of **analytical constructs such as Space-Time Prism and Space Time Paths** which informs the development of analytical constructs of **person-based accessibility**.

Although there is active research following similar lines, there are limited explorations in the ability to examine changes in urban environment – an important quality for an analytical construct for spatial design - with PESASP (1976, 1978) MASTIC (Dijst, 1995) being the most aligned. At the same time, given that there are technological advancements in Geographical Information Systems explored by Kwan and others (Kwan and Hong, 1998; Chen and Kwan, 2012) for geographical studies, it is worth re-contextualising and extending the analytical construct back into the realm of urban spatial design. This re-contextualisation will aim to contribute to the discussion in the shift from mobility to accessibility (Levine, Grengs and Merlin, 2019) and from accessibility to sustainable accessibility (Couclelis, 2000) towards normative interpretations of people-based sustainable accessibility.

1.7 Research position

The transport integrated city design involves considerations in spatial functions and transport systems. Spatial functions and transport systems are interdependent and influences travel activities within a city.

City design processes can be "informed by more rigorous and objective methods" (Karimi, 2012) and supported by analytical methods (Bertolini, le Clercq and Kapoen, 2005).

There are multiple analytical approaches currently employed for the analysis of alternative city designs related to sustainable transport systems and to support sustainable travel activities. Different analytical approach has different considerations in terms of what is included, spatial scale of interest and analytical result of interest.

The current analytical approach in city design is limited in the understanding of passenger transport. An understanding of passenger transport within a mix of other travel modes is essential to sustainable transport systems and supports sustainable travel activities in an architectural urban scale.

There is a lack of appropriate computational analytical constructs in architecture for the modelling and analysis of opportunities for the use of travel modes in alternative urban condition.

The constructive research approach will be used in this study to construct a computation enabled analytical framework to the domain-specific problem. The computation enabled analytical framework contributes to city design towards sustainable transport system and to support sustainable travel activities by facilitating the comparison of travel modes for comparative assessment of multiple alternative future urban scenarios.

Chapter 2 - Literature review

2.1 Chapter introduction

The literature review aims to answer the research question: What are the theoretical knowledge and considerations to support an appropriate computational analytical construct for ex-ante analysis of alternative urban conditions towards sustainable transport systems and support sustainable travel activities?

The research question is separated into three sub-questions:

1) What are known conceptualisations of transport and travel analysis in academic literature?
2) What are the analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions?
3) How do the analytical approaches relate to notions of transport/travel-related sustainability?

This chapter is in two sections corresponding to the first two sub-questions, followed by a synthesis to answer the third sub-question.

The first section (2.2) identifies known conceptualisations of transport and travel analysis in academic literature. This section aims to identify approaches and conceptualisations in fundamental research for transport and travel analysis.

The second section (2.3) identifies known analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions through a state-of-the-art review of relevant computational analytical constructs in the past 20 years from multiple city-related disciplines.

Analytical constructs to facilitate scenario modelling and diagnostic assessment of alternative urban conditions rely on known relationships between what is being modified in alternative urban conditions and what is being measured and made visible through the analytical approach. The first section provides the background context in transport and travel-related analysis necessary to understand the underlying theoretical assumptions in different ex-ante analytical approaches in the second section.

The two sections are combined to synthesize the two sections in the literature review and to align the literature with different notions of transport and travel-related sustainability discussed previously in section 1.3.3 pg31. First, on the relationships between what can be made visible (section 2.2 pg71) through different ex-ante analytical approaches on alternative urban conditions (section 2.3 pg89). This results in the identification of three fundamental-applied research approaches (section 2.4.2 pg104). Second, on what can be assessed ex-ante corresponding to different notions of transport and travel-related sustainability (section 1.3.3 pg31). This results in the identification of three analytical approaches towards sustainability relevent to transport-integrated city design (section 2.4.3 pg105).

The literature review concludes with the space-time approach (as a fundamental-applied research approach) to accessibility (analytical approach towards sustainability) as most aligned with the research motivation and problem (section 1.6 pg62). Research gap in space-time approaches for ex-ante analysis is identified and selected for further investigation.

This chapter corresponds to step two in a constructive research approach in a later section (pg144), with a corresponding objective to obtain a general and comprehensive understanding of the topic of the analysis of transport system and travel activities towards sustainability in built environments and future built environments.

2.2 Background context in transport and travel-related analysis

2.2.1 Introduction

Before proceeding to a review of computational analytical constructs relevant to the topic of the study, there is a need to understand the underlying background context of how transport and travel are understood in the literature related to design and planning. One of the primary sources of model-based analysis, relevant to the analysis of future conditions, is transport modelling (Ortúzar and Willumsen, 2011). The term “travel behaviour” found in transport modelling literature is used as a starting point of the exploration of the topic.

2.2.2 An overview of literature on travel behaviour

An exploratory literature search was conducted with an aim to locate main groups of literature within the topic area of “travel behaviour” for a general understanding of the topic. The search was conducted with the following keywords: “travel behaviour” OR “travel behaviour” as a topic search on the Web of Science database for articles between 1997-2017. The search returned 3707 results, out of which 3605 entries contain abstracts. The analysis is conducted in three phases: the first phase utilises a well-known bibliometric software tool vosviewer (van Eck and Waltman, 2010), the second phase involves further reading and interpretations, and the third phase attempts to identify theories and models that can or have been underpinning computational analytical constructs.

Five main overlapping groups were identified through content analysis by the co-occurrence of terms used within the title and abstract between articles using vosviewer. The co-occurrence of terms used between articles is assumed to indicate that there are some similarities between the articles. The groups of keywords within each group were interpreted by identifying 1) topics 2) data sources 3) types of methods and 4) types of analysis. The groups were then labelled by the themes of the group of keywords.

Group	1	2	3	4	5
General aim	**Policy**	**Environmental**	**Choice and preference**	**Activity pattern**	**Big data**
Topics	Climate change	Active travel	Activity generation	Activity travel behaviour	Communication
	Behavioural change	Commute mode choice	Choice process	Behavioural response	Communication technology
	Environmental sustainability	Neighborhood design	Decision making	Commuting behaviour	Global positioning system
	Sustainable development	Residential choice	Location choice	Trip chaining behaviour	ICT
	Economic development	Land use policy	Mode choice	Mode split	Human mobility
Data source	Not specified	Cross sectional data	Stated preference survey	Activity diary	Census data
		National household travel	Preference survey	Day travel diary	Diary
			Activity schedule	Household survey data	GPS data
				Household travel survey	Land use data
				Travel diary data	Mobile phone data
				Time use	Smart card data
					Travel behaviour data
Methods	Depth interview	Cross sectional study	Behaviour model	Conceptual model	Statistical model
	Online survey	Longitudinal study	Choice model	Linear regression model	
	Questionnaire	Structural equation model	Demand model	Structural equation model	
	Policy scenario		Discrete choice model		
	Literature review		Microsimulation		
	Structural equation model		Mixed logit model		
Analysis	Qualitative analysis	Covariate	Revealed preference	Exploratory analysis	Classification
	Descriptive statistics	Causality	Stated preference	Descriptive analysis	Clustering
	Quantitative analysis	Logistic regression	Policy analysis	Path analysis	
		Principle Component		Linear regression	

Figure 7 Identification of topics, data, methods, analysis from further reading

2.2.2.1 Identified themes related to” travel behaviour” in literature

1. Policy

Group 1 has the general theme towards **policy** goals characterised by topics of climate change, behavioural change, environmental sustainability, sustainable development, and economic development.

2. Environmental

Group 2 has the general theme in environmental issues characterised by topics of active travel, commute mode choice, neighbourhood design, residential choice, and land use policy.

3. Choice and preference

Group 3 has the general theme in studies of choice and preference characterised by topics of activity generation, choice process, decision making, location choice, and mode choice.

4. Activity patterns

Group 4 has the general theme in studies of activity pattern characterised by topics of activity travel behaviour, behavioural response, commuting behaviour, trip chaining behaviour, and mode split.

5. Methods of data collection

Group 5 has the general theme in studies related to data collection characterised by topics of communication, communication technology, Global Positioning System (GPS), Information and Communication Technology (ICT), and human mobility.

2.2.2.2 To estimate or to measure?

Two types of research can be identified. The first being a **study of past activities**, including studies that seek to understand or explain the relationship between **observed travel patterns** and other variables of interest, or studies of trends from observed travel patterns over time. The second being an **estimate of future activities**, related to studies and/or the development of models related to **travel behaviour** that results in travel activities and travel patterns.

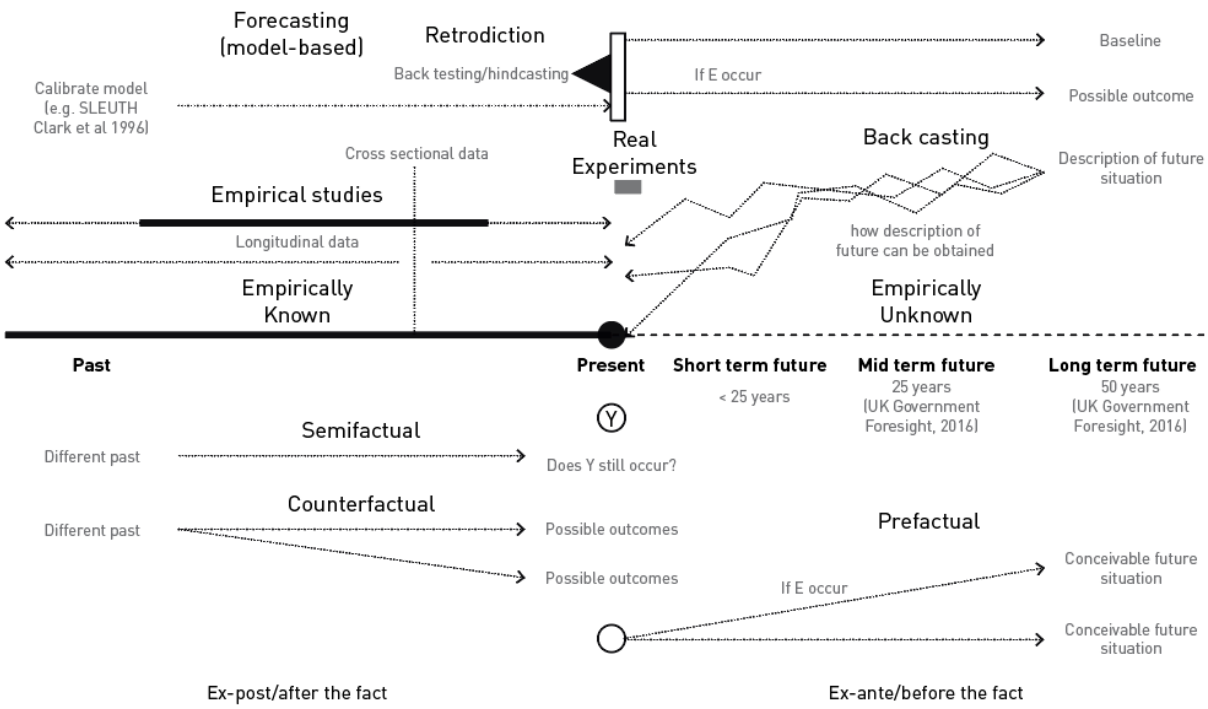

Figure 8 After the fact measure, estimation and different types of reasoning for unrealised conditions

The following section attempts to understand the types of research studies in relation to the motivation of this study to analyse alternative urban conditions for transport-integrated city design. The relevant groups relate to the estimation of futures are identified further discussed.

Policy (group 1) includes studies towards the estimation of travel activities for scenario analysis at the policy level. For example, Daly et al. (2014) employ modelling to project future aggregated travel activities and a study using a land-use transport integrated framework in the context of Madrid, three policy scenarios were simulated and evaluated (Alonso and Wang, 2017). Other studies in this group that do not relate to direct quantitative measurement or estimation of travel activities include behavioural change at an individual level. They consist of the design of behaviour change measures (Avineri, 2012) and studies in attitudes and beliefs of individuals, such as models towards electric vehicles adoption for policy scenarios (Beck, Rose and Greaves, 2017).

This group also contains papers that discuss and highlight limitations in behavioural change (Barr and Prillwitz, 2014).

Environmental (group 2) and Methods of data collection (group 5) are most relevant to the measure of past activities. Environmental (group 2) focused on analyses of observed travel patterns against other variables such as neighbourhood design and land use patterns. Methods of data collection (group 5) is characterised by studies in new methods for data collection, contributing to measurements of travel activities.

Choice and preference (group 3) and activity patterns (group 4) are of particular relevance to the estimation of future activities in relation to travel behaviour that results in travel activities and patterns with the measure of past activities. Choice and preference (group 3) is characterised by the methods and analysis of travel decisions of individuals, and group 4 is characterised by methods and analysis of activity patterns of individuals.

2.2.2.3 Travel decisions of individuals

Group 3 Choice and preference

Studies that focus on the travel decisions of individuals are centred on the analysis of choice and preferences with economics and psychology as the two significant sources of theory.

Rational choice theory from economics, conceptualises choice as a decision between alternatives according to preferences under constraints. Revealed preference and stated preference are two different ways to study preferences in empirical research. The common underlying theory of preference is utility theory, which enables preference to be quantified as “utility” from empirical research and constructed as a utility function. In other words, a mathematical model of preference referred to as choice models. One of the foundational analyses based on economics in the travel decisions of individuals is discrete choice analysis, a model developed by McFadden (1974) for the studies of travel mode choice alternatives. This perspective aims to describe, explain, and predict individual travel decisions as discrete choices with the decision based on the utility of available alternatives. It is commonly applied to mode choice analysis and mode choice modelling (Ben-Akiva and Lerman, 1985).

Psychology offers another perspective on the travel decision of individuals. In general, preference refers to an individual attitude towards a set of alternatives with a focus on the decision process. A commonly cited theory applied in travel behaviour studies is the Theory of Planned Behaviour (TPB) (Ajzen, 1991). TPB contains three aspects in its construct: attitude towards the behaviour, social norms and perceived control of behaviour. A common use of TPB is in predicting mode choice, usually paired with structural equation modelling, typically in transport psychology. (Bamberg, Ajzen and Schmidt, 2003) Others apply TPB as a theoretical basis for studies that aim towards policy or strategies for behavioural change. A notable example of a study based on TPB was conducted by Anable on mode choice behaviour on day trip travel to leisure attractions with a scoring construct based on TPB of a sample population followed by cluster analysis. Indicators of travel behaviour and personal characteristics within each cluster were then discussed against policy instruments. (Anable, 2005)

2.2.2.4 Activity patterns of individuals

Studies that focus on activity patterns of individuals are centred on the analysis of and generation of **activity schedules** as a formative aspect of travel activity patterns. The underlying view is that travel activity is 'derived' from other activities that are observable by a record of individuals' travel activities as well as other activities. (Weiner, 2016) The identification of data sources in the exploratory literature search includes household travel surveys, travel diary, time use, and activity diary. Depending on the data source, it allows for studies not only of the patterns of individuals but patterns of multiple individuals, for example, within a household.

2.2.2.5 Discussion

Policy (group 1) includes models that are developed for policy scenarios, but not all models are directly related to travel activities at a fundamental research level. There is a mixture of qualitative (e.g. interview) and quantitative approaches (e.g. SEM) as well as non-empirical approaches (e.g. policy scenario).

Models in group 1 that are related to travel activities use methods in group 3. For example, a stated preference survey was used to study travel mode to school with three policy scenarios for modal shift tested using a mode choice model. (Kamargianni, 2015) An example of a non-empirical approach to analyse policy scenarios employs a simulation model using a traditional four step model (to be described in a later section) with a discrete choice model for mode choice modelling. Emissions are estimated based on a modal split that is sensitive to policy scenarios for density, diversity, travel cost, and time. (Rahman and Idris, 2017) Another example tests for cordon toll, public transport improvements, teleworking, and re-densification. (Alonso and Wang, 2017)

There are examples of studies that discuss the potential of (Malayath and Verma, 2013) and employ (Wang, Shao and Ji, 2017) activity-based approaches for policy analysis, an example of policy scenario from Wang et al. is the effect of policies that **increases trip time** on **energy consumption**. There are potential relationships between group 1 and group 5 (data) for validation of new model system towards policy analysis (Bernardin *et al.*, 2017)

It is known that methodological developments in transport-related research, especially in the estimation of future travel demand, are often seen as developments parallel to policy concerns. This is evident in a shift in focus from aggregated transport demand modelling which was originally developed for forecasting long term demand and road building, to disaggregated travel demand models and activity-based travel demand models that are more sensitive to policy requirements for travel demand management. (McNally, 2000b; Rawoof and Bhat, 2011) These types of studies typically set out as a model of existing conditions as a baseline with several policy scenarios tested and compared against the baseline.

Policy scenarios developed in the simulative studies aimed towards **environmental sustainability** (group 1) are based on studies in land use parameters (group 2) such as density and diversity, and studies in choice and preference (group 3) with typical models of discrete mode choice and parameters such as travel time and cost. (group 1) The focus primarily on environmental sustainability is said to be at the expense of other dimensions of **sustainable development,** including social exclusion (Kamruzzaman, Hine and Yigitcanlar, 2015) and accessibility (Silva, 2013). The studies of activity patterns (group 4) suggest possible means to understand the tension between the sole aim of reduction of GHG emissions as environmental criteria and social criteria such as the “feasibility of activities, travel patterns, and travel time” (Ritsema van Eck, Burghouwt and Dijst, 2005).

2.2.2.6 Overview of literature on travel behaviour: section conclusion

An observation from the set of literature is that the term “travel behaviour” refers to “behaviour” in general terms and does not necessarily contain specific association to specialised fields in behavioural sciences.

The overview of literature related to travel behaviour identifies five main research areas with different but interconnected purposes and aims that connect the study of travel behaviour to various fields of study. These include 1) issues of sustainability with studies related to policy goals and strategies for sustainable development, 2) environmental issues associated with urban planning, neighbourhood design studies and debates on sustainable urban forms, 3) methodological developments and analytical studies in choice and preference analysis and modelling, 4) methodological developments and analytical studies in activity-based approach to analyse travel behaviour and 5) emerging technology that supports data collection.

There are known limitations to the approach taken to conduct this literature overview. The primary limitation is that this approach only reveals the dominating groups of literature by reducing the dimensions of the variations of research, specifically especially emerging topics are not represented. The second limitation is that there is a mixture of empirical, non-empirical model-based studies as well as theoretical articles included that are not visible from the way in which the studies are grouped. Nonetheless, this serves as an overview for a broad understanding and contributes to a further understanding of this topic, especially for an audience who may not be familiar with the wide variety of academic research related to travel behaviour.

2.2.3 Modelling approaches in transport/travel analysis

This section describes the background context for an understanding of the two dominant modelling approaches for transport and travel analysis. These two approaches are related to choice and preference (group 3) and activity patterns (group 4) found in the overview of travel behaviour.

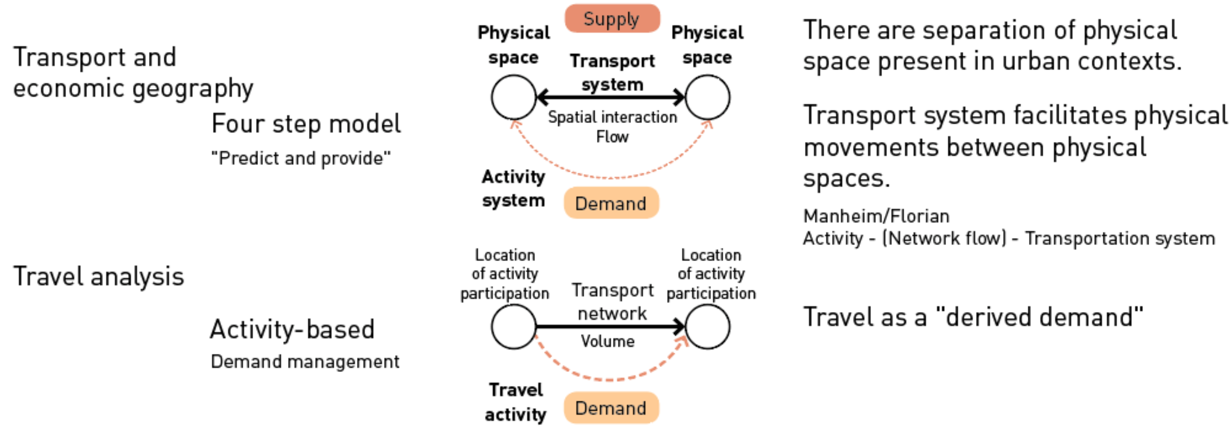

Figure 9 Diagram showing the main differences in a four step model and an activity-based model at a system level

2.2.3.1 Four step modelling approach

There has been a long history of development in the four step model as an approach for travel demand modelling (McNally, 2000b). It has been and is currently applied in both transport planning practice for forecasting transport demand and in academic studies embedded within simulation systems such as MARS (Pfaffenbichler, 2003). It is useful to understand what is involved in a conventional four step model as a reference to alternative approaches. A four step model, as its name suggests, contains four steps, and each step is described in general as follows based on the description from a number of published sources (McNally, 2000b; Ortúzar and Willumsen, 2011; Hollander, 2016).

Step 1: Trip generation

Trip generation refers to the generation of origins and destinations of trips. The origins and destinations is commonly defined as transport analysis zone (TAZ) as a spatial unit. Each zone is defined as a production zone - where people would exit the zone or a attraction zone – where people would enter the zone.

Step 2: Trip distribution

Trip distribution refers to the number of trips between origin zones and destination zones. A spatial interaction model can be used in this step.

A spatial interaction model is a mathematical model that aims to predict the movements between origin and destination. An early model used is the gravity-based model. A gravity-based model assumes the interaction between production and attraction is related to the size and distance in-between. The destination choice model, based on random utility theory, is an alternative to the gravity-based model as a relatively disaggregated approach.

Step 3: Mode split

Mode split refers to the percentage of different modes of transport between TAZ. For example, private motorised transport and public transport in general, or in more detail, formulations of different types of public transport such as bus, tram, and train.

A number of different models are used to estimate the mode split. These are the direct generation model, trip-end model, trip-interchange model, and logit-based models. The models differ in the data requirements and level of aggregation.

A direct generation model estimates mode split based on population density. A theoretical assumption is required in this case, for example, the higher the population density, and the higher public transport ridership.

A trip-end model typically incorporates the population density of each analysis zone and socio-economic characteristics data such as income and car ownership. Each trip is defined by its trip purpose e.g. trip ends at home or trip ends at work. This is done before the trip distribution step, and hence trip specific characteristics are not considered.

A trip-interchange model is done after the trip distribution step and includes the characteristics of the trip. A utility-based impedance factor is then calculated per mode. This can include in-vehicle time, excess time, cost and income. The impedance factor is then converted into a percentage of the total impedance factor of all modes as an estimated mode split.

In a logit-based model, a value for each mode is calculated using a utility function and a logistic function is applied to estimate mode split. The utility commonly consists of travel time, cost but it can also include other factors such as in-vehicle time, walk time, wait time, number of interchanges. When there are only two choices, a binary logit model can be used. When there are multiple choices, a multinomial logit (MNL) or nested logit is used.

As stated above, a disaggregated model considers trip-specific characteristics. The trip characteristics are processed as utility or disutility. The characteristics in consideration vary when applied in context, depending on what is to be modelled. For each of the characteristics considered, a corresponding data set or method of extracting the data needs to exist. This adds to the data requirements to compile a working model in context.

Step 4: Route assignment

Route assignment refers to the selection of routes for each trip. The simplest form of route assignment is all-or-nothing. In an all-or-nothing assignment, the route for each origin-destination pair is computed using a pathfinding algorithm, normally by the shortest travel time. The volume of traffic as an effect of multiple trips travelled along the same route segment is not considered.

A typical approach to route assignment is “user equilibrium” and “system optimal”, principles described by Wardrop and Whitehead in 1952. User equilibrium is a state where “no driver can unilaterally reduce his/her travel costs by shifting to another route”. In system optimal, “drivers cooperate with one another in order to minimize total system travel time” (Wardrop and Whitehead, 1952).

The steps are usually described in this sequence. In practice however, some of the steps are in a different order depending on the question to be answered. For example, the UK standard guidance suggests a sequential step of trip generation, mode split, trip distribution, and route assignment (Hollander, 2016).

2.2.3.2 Activity-based approaches to travel analysis

Activity-based approaches have been developed as a response to the increasing individual-oriented transport policy needs and a response to the limitations of the four step approach of conducting analysis in transport systems with a shift towards travel activities. (McNally, 2000a) Activity-based approaches are disaggregated (Iacono, Levinson and El-Geneidy, 2008), sometimes described as finer grain (Gerber *et al.*, 2018), higher resolution (Wegener, 2000), high fidelity (Miller, 2014) models of both space and human activities. This section describes the historical development and origins of activity-based approaches, gives an overview of types of identifiable approaches, analysis of the spatial representation of the models followed by a discussion against the research aims posed in this study.

Hägerstrand’s time geography (Hägerstrand, 1970) is a commonly cited reference in the literature referring to the origins in the underlying theoretical concepts and constructs that informs activity-based approaches. In brief, time geography postulates that an individual’s activities are limited by three types of constraints where space and time are central: (1) capability constraints (2) authority constraints, and (3) coupling constraints.

The combination of concepts from a transport and urban planning context (Cullen and Godson, 1975) gives rise to three interrelated concepts:

(1) Activity pattern - individual activities and time allocation subject to individual and societal constraints, for example, the requirement to be at work at a specific time (authority constraints) to meet someone (coupling constraints) and the spatial, physical accessibility constraints affects the time and type of travel activities (capability constraints).

(2) Spatial distribution of opportunities for activity participation (authority, capability and coupling constraints), and

(3) Temporal constraints on accessibility, for example, a library has defined opening hours for a particular day (authority constraints), bus services only run at specific intervals, and time required to traverse the distance in time (capability constraints) for activity participation (coupling constraints).

One of the first applications of time geography concepts in the analysis of travel activities for urban planning can be traced back to Lenntorp's Program Evaluating the Set of Alternative Sample Paths (PESASP) (Lenntorp, 1978). This approach is different from the use of time geographic notations to describe movements in space and time. Descriptive time geography places emphasis on describing known space time paths of individuals of a population, and a set of analytical concepts (such as "bundles" and "coupling constraints") can then be applied. PESASP differs in that instead of a description of known space time paths, multiple feasible space time paths are "simulated" from narratives of individuals' daily activity programmes. The daily activity programmes are then translated to time geographic language as a description of time, and a computer model is used to search for possible combinations within a physical spatial urban context. The purpose of PESASP is not to predict but to understand the implications of changes in the built environment or changes in transport schedules with considerations of an individual's space time constraints expressed through daily activity programme.

One of the first known use of time geography concepts in transport planning has been attributed to Jones (Jones, 1983) known as "human activity approach" with a focus in the study of activities patterns in relation to travel behaviour. It provides a different perspective by including the considerations in activities under constraints and other activities in daily life in understanding travel behaviour that was previously only considered as rational choice (McFadden, 1974). The use of trip chains to describe the inter-linkages between different activities is utilised instead of using solely trips as a unit of analysis. (Fox, 1995)

Jones suggested a framework of studying travel behaviour that is based on previous lines of studies. These studies include choice process, time budget, time allocation, timing and sequencing of activities, time geographic framework, space time constraints and interpersonal linkages, with a focus on the pattern of time and space-use where activity participation and household organisation is central to the analysis. Jones proposed and prototyped an activity-based "simulative" model named Household Activity Travel Simulator (HATS) as an interview-based survey technique to study household travel patterns.

The HATS technique consists of a display board with a map as the spatial representation and an empty daily schedule with three separate rows for non-home activities, travel activities, and home activities. The first stage in the interview procedure is to understand and represent the existing behaviour of the interviewee in terms of daily activity patterns. In the second stage, the interviewer introduces a proposed change affecting elements in space and/or time, and the interviewee is asked to respond to the hypothetical changes by rearranging the schedule on the display board. The third and final stage is an examination of the impact of change by the interviewee on their daily lives, and the proposed change is evaluated.

PESAPS is labelled as constraint-based model (Timmermans, Arentze and C.-H. Joh, 2002b) and is the first of its kind amongst others that follows. Other constraint-based models include Combinatorial Algorithm for Rescheduling Lists and Activities (CARLA) based on HATS introduced earlier and Model of Action in Time Intervals and Cluster (MASTIC) (Dijst, 1999). The main focus of HATS is the ability to evaluate changes in the built environment and its effect on activity programmes that would have originally been possible.

Although the constraint-based model can provide an understanding of individuals' space and time constraints and implications of changes, it is not used for the purpose of estimating the number of future activities on its own.

The purpose of prediction in transport planning is mainstream implicit in the development of the travel demand model. The underlying constraints-based approach is used as part of larger frameworks aimed at modelling travel demand. Such frameworks include the Prism-Constrained Activity-Travel Simulator (PCATS), GIS-Interfaced Computational process modelling for Activity Scheduling (GISICAS) and more recently Forecasting Evolutionary Activity-Travel of Household and their Environmental Repercussion (FEATHERS) (Bellemans *et al.*, 2010).

Others have since incorporated known methods that have already been developed for travel demand modelling such as the utility-based models and developments of new methods such as the computational process models based on activity-based approaches towards travel demand modelling. (Rasouli and Timmermans, 2014)

Both utility-based models and computational process models are used to model choices and decisions that are not directly measured specifically in terms of activity generation, as identified in the overview of literature on travel behaviour section 2.2.2. Another common characteristic is that a constraints-based approach is used to narrow down feasible alternatives based on the space time constraints and the formulation of “choice set”- a set of possible alternatives in utility-based models and computational process models.

Utility-based models follow the tradition from econometric developments in the analysis and modelling of mode choice and route choice. The utility-based approach is extended to the study of activity patterns as models of the choice of activities schedules within a day. One of the first models of this kind is from Alder and Ben-akiva in 1979. The model starts with a set of complete daily activity schedules (choice set / alternatives). Each schedule contains a number of quantified characteristics, and choice is assumed as the daily activity schedule with maximum utility. (Alder and Ben-akiva, 1979) The simulation of Travel/Activity Responses to Complex Household Interactive Logistic Decisions (STARCHILD) (Recker, McNally and Root, 1986) is similar to Alder and Ben-akiva's model with considerations in feasible space time paths of household members and network travel speed. Bowman and Ben-akiva took the choice process further. Instead of a full-day schedule, it is divided into tours – a trip chain that starts and ends at home. The choice process is choosing alternatives between the primary trip purpose and the set of tours available to fulfill the trip purpose. (Bowman and Ben-akiva, 1996)

Computational Process Models are rule-based models and aim to provide a more realistic representation of the human decision-making process than a utility maximisation assumption. A heuristic or rule-based model allows for a representation of a decision process that is satisficing rather than optimising. One of the first models of this kind is SCHEDULER (Garling, 1989). A sequential activity generation process is described where one starts with a decision on an activity and in consecutive choice of activity from a set of activities based on heuristic rules. The choice of activities has been extended to include space time constraints with a GIS-based constraint-based approach in GISICAS. (Golledge, Kwan and Garling, 1994) A Learning Based Transportation Oriented Simulation System (ALBATROSS) (Arentze and Timmermans, 2000) is an example of the use of a computational process model that is in operation and under constant development. ALBATROSS is a travel demand simulation system within which there is an activity generation module that uses a sequential activity generation process. The heuristic rules are formulated as a decision tree – a hierarchical set of rules - and in ALBATROSS the decision tree is formulated by analysing travel activity data.

A core notion in activity-based approaches is the “spatial-temporal and institutional constraints set by the environment”. (Arentze and Timmermans, 2000) Although most models include the considerations of space time constraints, they are interpreted in different ways in different models.

Some models made explicit use of the classical time geography concepts of space time path (e.g. STARCHILD) and space time prism (e.g. MASTIC and PCATS (Kitamura and Kuwahara, 2005)). The classical time geography concept of space time path and prisms in this context can be understood as areas accessible within a given time based on the maximum speed of travel at a certain location. It assumes no transport network influence and assumes an isotropic radius of the accessible area from a location (or in time geography term “station”). Models using a space time path or prism approach require point-based spatial representation for locations.

Some use the notion in broad terms, such as ALBATROSS in terms of different types of identifiable constraints. This includes situational (people cannot be in different locations at the same time), institutional (opening hours), household (coupling), spatial (locations of activity participation), time (activity duration), spatiotemporal (travel time and activity start time) constraints within an environment in the context of a model of activity generation. Models such as ALBATROSS are aimed specifically at activity generation and the spatial-temporal constraints are supplied as data inputs as a description of the environment the spatial dimension is not explicitly stated. However, from its application in producing “trip matrix” (a common method used in four step models) it is possible to understand it as a zone based model.

Three types of spatial units can be identified from the described application of the models: (1) Grid cells (2) Zones and (3) Points.

- PESASP (Grid cells centroids from the applied example in the study of locations of day nurseries, work places and 62 sampled dwellings locations plus the public transport network in Karlstad)
- GISICAS – Zones to centroids
- ALBATROSS - Zones
- MASTIC (Facilities location as clusters from the applied example in Zoetermeer (Dijst, de Jong and van Eck, 2002))

Some of the models are designed primarily for research purposes and not for general application. For example, STARCHILD was developed to examine trip chaining behaviour. (McNally, 2000a) Some have attempted to demonstrate possible applications related to policy issues. For example, GISICAS was developed "to describe the basic spatiotemporal pattern of household travel behaviour" and demonstrated its application through "the changes in travel behaviour due to telecommuting". (Golledge, Kwan and Garling, 1994)

Although all types of modelling approaches can be develop to inform planning or policy decisions, different types of modelling approaches have a tendency to focus on specific kinds of policy or planning issues.

Modelling approaches have an influence on the specification of the model. The specification of the model, including the type of processes and entities represented in the model and the representation of results from the process, determine the sensitivity to policy or planning instruments and policy or planning goals. In other words, sensitivity to policy is a question of "what can be changed in the model?" The end results from the process are a question of "can the change produce the intended consequences in the model?" both of which are problems of model specification. In addition, all models in a travel demand modelling context aimed at an estimation of the number of travel activities require theory-based processes, and a background understanding of the underlying theories to be able to interpret the results and to understand the limitations in the model.

A transport-integrated city design issue is the spatial distribution of activities at a high spatial resolution - for example, residential locations, facility and amenity locations. The constraint-based models, as described, are the most relevant in connecting spatial functions and travel activities within an urban environment without strong behavioural assumptions such as utility-maximisation.

2.2.4 Accessibility

2.2.4.1 What is accessibility? – a brief overview

Accessibility means different things to different people in different contexts with different frames of reference. In an urban-transport context, urban accessibility can be:
(1) the ease of access by persons with disabilities to elements or physically challenged within the built environment or "facilities designed to accommodate people with disabilities in pedestrian planning and facility design" (Byars, Wei and Handy, 2017) and

(2) the relative ease of reaching a particular location or area in the city or "ease with which people can reach destinations such as jobs, shopping, and leisure-time activities" (Byars, Wei and Handy, 2017). A broader definition is the ease of access facilitated by connections between land use, including rural areas not limited to the city. This study refers to the latter definition of accessibility that is the **relative ease of reaching destinations**.

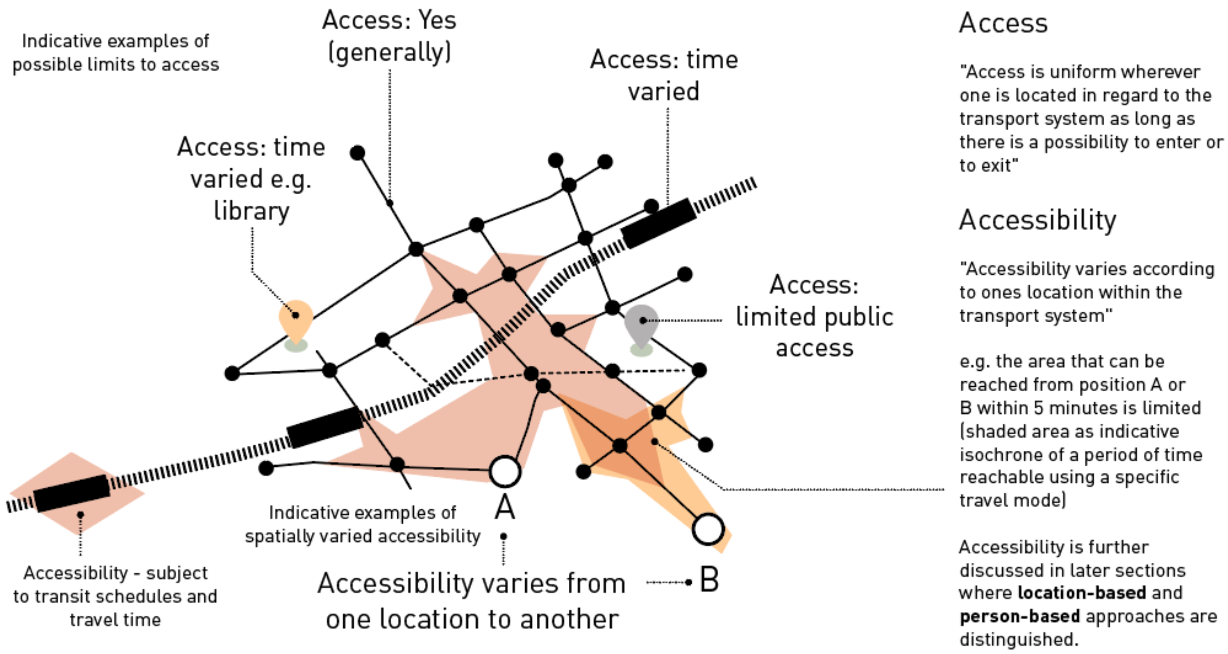

Figure 10 Differences between "access" and "accessibility" (Rodrigue, Comtois and Slack, 2016)

UK Department for Transport (DfT) views accessibility under two main definitions: 1) accessibility as land use and **connectivity** or 2) accessibility as the usability of the transport system for people with physical and hidden disabilities. The first definition is mostly used in economic cost-benefit analysis for project appraisals and takes the definition of accessibility as connectivity and land use. Non-monetised impacts include public transport accessibility indicators, for example, in London (PTAL).

There is **no single definition** of urban accessibility. (Rietveld and Bruinsma, 1998) "There are no universally acknowledged definition of accessibility indicators with different theoretical backgrounds have use proposed and implemented in empirical investigations" (Baradaran and Ramjerdi, 2001). Various conceptual definitions have been proposed over time. These include "potential of opportunities for interaction" (Hansen, 1959), "ease of spatial interaction", "potentiality of contacts with activities or supplies" (Weibull, 1980), "the ease with which any land-use activity can be reached from a location using a particular transport system" (Burns and Golob, 1976) and "the benefits provided by a transportation/land-use system" (Ben-akiva and Lerman, 1979). Furthermore, there are various operationalised and technical definitions such as “attractiveness of a node in a network taking into account the mass of other nodes and the costs to reach those nodes via the network” (Rietveld and Bruinsma, 1998)

There is, however, a common understanding that the concept of accessibility is defined and operationalised for specific research problems and applications (Kwan, 1998; Rietveld and Bruinsma, 1998) and that it is associated with the urban environment including the land use or the locations of activities and transport systems.

2.2.4.2 Why accessibility?

The concept of accessibility in urban transport is known to be used for research purposes in academic fields such as transport planning, urban planning and geography. For example, it is said to be an “important explanatory factor of geographic phenomena” and applied for analytical and evaluative purposes. (Kwan, 1998) It is also central to the understanding of cities as a system that recognizes the interdependencies between land use, transport, and cities as an evolving system that has been conceptualised as “land-use transport feedback cycle” (Michael Wegener, 2004) as an example.

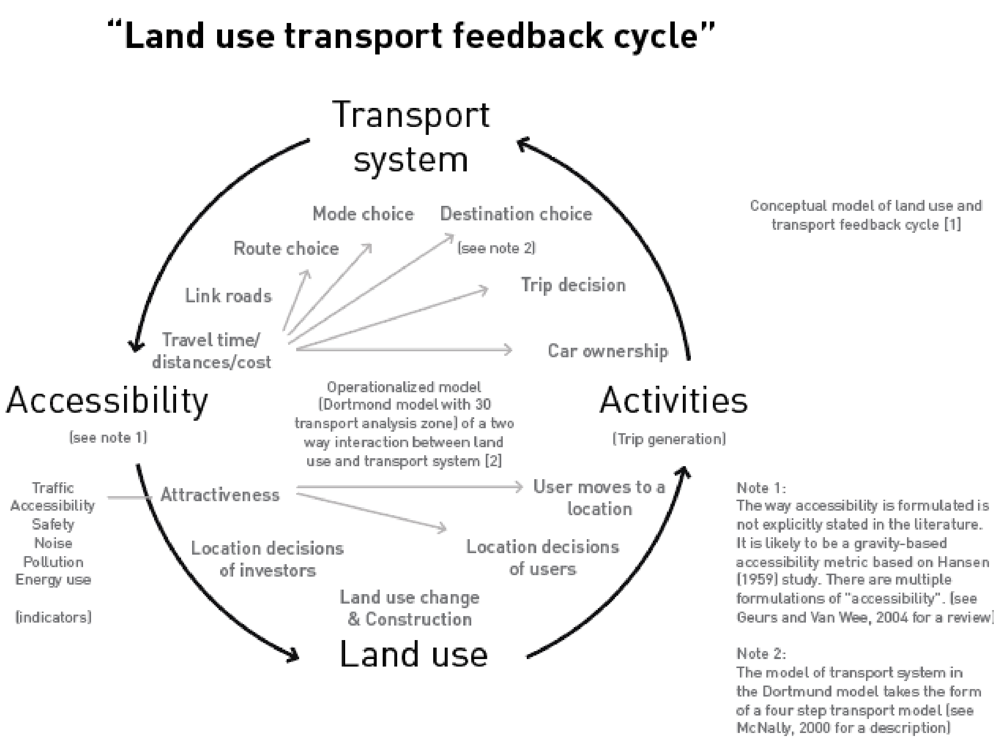

Figure 11 “land-use transport feedback cycle” (Michael Wegener, 2004) with example of operational model for each step (Wegener, 1996)

In addition, accessibility as a measure is useful for urban planning/spatial planning/spatial design/urban policy/spatial policy. It has been used as a metric for two purposes. Firstly, **to describe** the characteristics of an urban transport environment at a specific spatial resolution and secondly, **to provide insight to support** spatial planning/policy. (Silva *et al.*, 2015)

2.2.4.3 Literature review to understand different conceptions of accessibility
In order to obtain a broad understanding of the multiple operational definitions and concepts of urban accessibility in research reflecting different perspectives, a synthesis of literature reviews on accessibility measures is conducted.

Pirie's article in 1979 is one of the first reviews of multiple accessibility measures, which provides an overview and classification of the kinds of measures used. (Pirie, 1979) Pirie defines a broad distinction of aggregated and disaggregated measures. Aggregated measures include 1) distance measures 2) topological measures 3) gravity-based measures 4) cumulative opportunity measures and disaggregated measures include 5) space time measures.

Two further reviews that cover the broad range of accessibility measures were found using the classification suggested by Pirie. Studies of operational comparisons are not included in this section - for example, Kwan's detail comparison of gravity-based, cumulative-opportunity, and space time measures (Kwan, 1998). A summary of the classification suggested that each review is described, followed by a synthesis of the classifications and a detail description, including an example of each type of measure.

Markri and Folksson (Makri and Folkesson, 1999) suggested three main types of measures based on previous literature: 1) place based measures (similar to Pirie's aggregated measures), 2) individual accessibility measures (similar to Pirie's disaggregated measures) with an additional type of 3) Space Syntax analysis.

Place based measures are measures associated to locations derived from the pattern of land use and transport system. The measures typically include the components of land use in terms of the amount and location of activities and transport systems in terms of travel distance, time, and cost. Place based measures include distance measures, cumulative-opportunity measures, gravity-based measures, and utility-based measures.

Individual accessibility measures estimate the accessibility by a particular person having particular monetary and time resources in other words, it has a unit of analysis of individuals as opposed to a location and that this accessibility can vary from person to person at the same location. Individual accessibility measures include space time measures.

Geurs and van Wee (Geurs and van Wee, 2004) suggested four basic types of measures associated with four perspectives: 1) **infrastructure-based measures** 2) **location-based measures** 3) **person-based measures** 4) **utility-based measures**.

Infrastructure-based measures are measures of a specific infrastructure such as average travel time and average speed. The type of measure is typically associated with measuring the performance of a transport system and used in transport planning.

Location-based measures include: 1) distance measures 2) contour measures e.g. cumulative-opportunity 3) potential/gravity-based measures 4) adapted potential measures 5) balancing factors measures. This type of measure is typically used in transport planning and geography studies.

Person-based measures include space time measures, which include further analytical developments of Hagerstrand's space time prisms by a number of researchers using the time geography approach since 1970s. This type of measure is used in geography studies, transport planning under the activity-based approaches.

Utility-based measures include: 1) logsum benefit 2) balancing factor benefit and 3) space time utility where one attempt was referenced to formalise and connect space time measure and economic benefit measure. This type of measure has its theoretical foundation in economics, and it has been applied in transport planning.

	Pirie 1979	Makri and Folksson 1999	Geurs and van Wee 2004
Infrastructure-based			Linneker and Spence 1992
Distance	Ingram 1971		Ingram 1971
		Guy 1977	
Contour			
Cumulative-opportunity			Guy 1983
	Wachs and Kumagai 1973	Wachs and Kumagai 1973	
		Oberg 1976	
	Mitchell and Town 1977		
		Black and Conroy 1977	
	Breheny 1978		
Topological			
Network analysis	Vickerman 1974		
Space syntax		Hillier and Hanson 1984	
		Hillier 1993	
		Hillier 1996	
Potential / Gravity-based	Hansen (Note 1) 1959	Hanson 1959	Hansen 1959
	Davidson 1977		
Adapted potential			Weibull 1976
Balancing factors			Wilson 1970
Space time	Lenntorp 1976		
			Miller 1991
			Dijst and Vidakovic 1997
		Kwan 1998	Kwan 1998
			Recker et al 2001
Utility-based			
Logsum benefit			Ben-Akiva and Lerman 1985

		Handy and Niemeier	1997		
		Sonesson	1998		
Balancing factor benefit				Williams	1976
				Martinez	1995
Space-time utility				Miller	1999

Classification colour coded for each column			Infrastructure-based
	Aggregated	Place-based	Location-based
		Space syntax	
	Disaggregated	Indiviudal-based	Person-based
			Utility-based

Table 6: Types of accessibility measures (Pirie, 1979; Makri and Folkesson, 1999; Geurs and van Wee, 2004)

Note 1: Hansen 1959 is commonly applied to express the relationship between land use system and transport systems in LUTI approaches to urban simulation

2.2.4.4 Discussion

There has been a number of past reviews on the topic of accessibility. Although there are different ways in which different authors classify different accessibility metrics. A clear distinction between the numerous ways to operationalise accessibility is **person-based** and **location-based** accessibility. Miller (2005) describes the difference between the notion of people-based and place-based accessibility. In this study, people-based is referred to as person-based, adopting Iacono et. al. (2008) terms when describing person-based accessibility as an area for further research in the context of land use transport integrated approaches. Place-based is referred to as location-based as “place” may invite unnecessary interpretations where place can mean locations with meaning. In short, **location-based** accessibility focuses on “spatial separation between key locations”, whereas **person-based** accessibility focuses on “measures that are directly tied to the individual in space and time”. Although most authors do not include utility-based measures in person-based approaches, Silva (2013) acknowledges that utility-based measures apply to individuals. However, there are key differences between the two approaches where utility-based metrics require an assumption of utility maximisation, and space time metrics are rooted in the limits and constraints posed by the space and time context.

The important distinction is between the assumption of utility maximisation and assumption of space and time as the limiting factor of movement. When the goal is not to produce a hypothetical-deductive model with back testing for validation in a LUTI context that cannot be achieved for accessibility, but to formulate a logical argument where conclusion follows premise, it appears to be challenging to formulate an argument based on utility maximisation as a premise outside the field of economics where it is generally agreed upon.

2.3 State-of-the-art review of computational analytical constructs for the analysis of potential travel activities in alternative urban conditions

2.3.1 Introduction

As identified in the background elaborated in chapter 1 and more specifically section 1.5 pg59-61, this study is motivated by the city design of alternative urban conditions and the need for a computation-enabled analytical approaches with the aim to support the assessment of alternative urban conditions for design decision making towards sustainable transport systems and to support sustainable travel activities.

This section aims to answer the research question (4b): What are the analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions?

A number of sources are included in the search for current computation-enabled analytical constructs. This includes CumminCAD (Cummincad, 1998), a specialised index of research articles for computational research for city design, as well as traditional sources that are informed by the background context.

2.3.2 Computational analytical constructs

This study views "computational analytical constructs" as artificial constructs that differ from natural phenomena and social phenomena. This section describes a framework informed by a design research perspective to analyse different computational analytical constructs by their theoretical foundations, operational models, method of analysis, and purpose. The scope of the review is limited to analytical constructs that are computational, relevant to the research motivations for city design.

This study adopts March and Smith's (1995) definition of (theoretical) **constructs, models, methods and instantiations** as types of research outputs and elements within artificial constructs from an information systems (IS) oriented design research perspective. Winter's (2008) interpretation and mapping to design-related research with theory as an additional link between construct and model (Winter, 2008) is included.

(Theoretical) constructs refer to concepts and entities with building <u>computational ontology</u>, for example, the data structure of a mathematical graph network includes a set of vertexes and edges.

Theory refers to <u>a set of propositions</u> expressing relationships between concepts and entities, with theory building as the main research activity to identify "cause-effect relationship" (Winter, 2008) or make use of "kernel theory" (Hevner *et al.*, 2004). Kernel theories are defined as "theories from natural or social sciences and serve as a foundation for artifact construction" (Fischer, Winter and Wortmann, 2010).

Model consists of an <u>operational set of propositions</u> expressing relationships amongst constructs, sometimes as an "embodiment of theory" (Batty, 1992) or, in other words, the operational model of the theory.

Method refers to a set of steps used to perform a task. Model and method are seen as "means-end relationship" (Winter, 2008) that connects constructs and theory which often results in an instantiation either as a tool or information system that the researcher operates or for a wider audience.

Instantiation refers to the tools or information systems in which the model and methods are operationised and produces outputs for interpretations or use as an application.

2.3.3 What is meant by computational analytical constructs in this review?

"Analytical construct**"** in this study includes models and methods connecting concepts and entities of interest (abstract constructs) and their relationships (theories) to the ability to perform analysis for further interpretations (instantiation). A focus on computational analytical construct implies the scope being limited to models and methods that is computable as supposed to physical and mechanical models.

More specifically, models and methods to perform ex-ante before the fact analysis on a number of alternative urban conditions as supposed to statistical analytical models on empirical data.

2.3.4 Aim and scope of the review

This review aims to provide an overview of what can be known from current analytical constructs in alternative urban conditions. Secondly, to identify the connections between current analytical constructs and different notions of transport/travel-related sustainability. Thirdly, to locate the research gaps in computational analytical constructs for alternative urban scenarios as well as its connections to different notions of transport/travel-related sustainability.

This review investigates a collection of twenty-eight computational analytical constructs related to potential travel activities from the past twenty years from multiple research fields, including transport planning, city design, geography, and urban studies.

2.3.5 Methodology

Analytical constructs to analyse **urban movements of people** in alternative urban scenarios were located from a search of published academic literature including **models, methods, and instantiations for analysis, instantiations as tools or information system.**

The review is structured around the identification of constructs, models, methods and instantiations as elements for each of the computational analytical constructs.

Elements within an artificial construct		
Theoretical constructs		What are the included entities?
	2.1	What is the representation of space?
	2.2	What is the representation of people?

Theory (kernel theory)	3	What are the relationships modelled between the included entities (space-people)?
Model and method	4.1	What are the main characteristics of the analytical construct?
Instantiation for analysis	4.2	What are the main outputs?
Instantiation for application	5.1	Is the analytical construct directly applicable for spatial planning/design/policy?
	5.2	What are the outputs towards spatial planning/design/policy?
	5.3	Why is the output useful for spatial planning/design/policy?

Table 7. Summary of elements to be identified from the review of computational analytical constructs.

The data gathered are organised in a tabulated spreadsheet with the name of the analytical construct, the year of first published, purpose, construct (space, people), theory of relationship between space and people, main characteristics, main outputs, outputs towards planning and policy, reference and academic field. (see appendix for the full tabulated spreadsheet)

2.3.6 Computational analytical constructs

	Name	Full name	Year (first published)	Reference
1	SUMO	Simulation of Urban Mobility	2001	Behrisch, M., Bieker, L., Erdmann, J. and Krajzewicz, D., 2011. SUMO–simulation of urban mobility: an overview. In Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind.
2	MATSIM	Multi-Agent Transport simulation	2008	Balmer, M., Meister, K., Rieser, M., Nagel, K. and Axhausen, K.W., 2008. Agent-based simulation of travel demand: Structure and computational performance of MATSim-T. Arbeitsberichte Verkehrs-und Raumplanung, 504.
3	MARS	Metropolitan Activity Relocation Simulator	2003	Pfaffenbichler, P., 2003. The strategic, dynamic and integrated urban land use and transport model MARS (Metropolitan Activity Relocation Simulator). Institute for Traffic Planning and Traffic Engineering.
4	LUTDMM	Land Use, Travel Demand Microsimulaton Model	2005	Xu, M., Taylor, M. and Hamnett, S., 2005. LUTDMM: an operational prototype of a microsimulation travel demand system. In 28th Australasian Transport Research Forum.

5	FEATHERS	Forecasting Evolutionary Activity-Travel of Household and their Environmental Repercussion	2007	Janssens, D., Wets, G., Timmermans, H. and Arentze, T.A., 2007. Modelling short-term dynamics in activity-travel patterns: the Feathers model.
6	ALBATROSS	A Learning Based Transportation Oriented Simulation System	2000	Arentze, T. and Timmermans, H., 2000. Albatross: a learning based transportation oriented simulation system (pp. 6-70). Eindhoven: Eirass.
7	PATRICIA	Predicting Activity-Travel Interdependencies with Suite of Choice-Based, Interlinked Analyzes	2002	Borgers, A., Timmermans, H. and van der Waerden, P., 2002. Patricia: predicting activity-travel interdependencies with a suite of choice-based, interlinked analyses. Transportation research record, 1807(1), pp.145-153.
8	CEMDAP	Comprehensive Econometric Microsimulator for Daily Activity-travel Patterns	2004	Bhat, C.R., Guo, J.Y., Srinivasan, S. and Sivakumar, A., 2004. Comprehensive econometric microsimulator for daily activity-travel patterns. Transportation Research Record, 1894(1), pp.57-66.
9	Aurora	Aurora	2004	Joh, C.H., Arentze, T. and Timmermans, H., 2004. Activity-travel scheduling and rescheduling decision processes: empirical estimation of Aurora model. Transportation Research Record, 1898(1), pp.10-18.
10	TASHA	Travel and Activity Scheduler for Household Agents	2005	Roorda, M.J., 2005. Activity-based modelling of household travel.
11	GABRIEL	Gis Activity-Based tRavel sImuLator	2006	Kwan, M.P. and Casas, I., 2006. Gabriel: Gis activity-based travel simulator. activity scheduling in the presence of real-time information. GeoInformatica, 10(4), pp.469-493.
12	ADAPTS	Agent-based Dynamic Activity Planning and Travel Scheduling	2009	Auld, J. and Mohammadian, A., 2009. Framework for the development of the agent-based dynamic activity planning and travel scheduling (ADAPTS) model. Transportation Letters, 1(3), pp.245-255.

13	DATA	Dynamic activity-travel assignment	2015	Liu, P., Liao, F., Huang, H.J. and Timmermans, H., 2015. Dynamic activity-travel assignment in multi-state supernetworks. Transportation Research Part B: Methodological, 81, pp.656-671.
14	DATA	Dynamic activity-travel assignment	2016	Liu, P., Liao, F., Huang, H.J. and Timmermans, H., 2016. Dynamic activity-travel assignment in multi-state supernetworks under transport and location capacity constraints. Transportmetrica A: Transport Science, 12(7), pp.572-590.
15		Connectivity of streets	2008	Peponis, J., Bafna, S., & Zhang, Z. (2008). The connectivity of streets: reach and directional distance. Environment and Planning B: Planning and Design, 35(5), 881–901.
16	UNA	Urban Network analysis toolbox	2012	Sevtsuk, A. and Mekonnen, M., 2012, March. Urban network analysis: a new toolbox for measuring city form in ArcGIS. In Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design (pp. 1-10).
17		DeCodingSpaces toolbox	2017	Abdulmawla, A., Bielik, M., Buš, P., Chang, M.C., Dennemark, M., Fuchkina, E., Miao, Y., Knecht, K., König, R. and Schneider, S., 2017. DeCodingSpaces Toolbox for Grasshopper: Computational analysis and generation of STREET NETWORK, PLOTS and BUILDINGS.
18		Reach analysis toolkit	2017	Feng, C., & Zhang, W. (2017). Grasshopper reach analysis toolkit: Interactive parametric syntactic analysis. In T. Heitor, M. Serra, J. Silva, M. Bacharel, & L. Silva (Eds.), Proceedings: Eleventh International Space Syntax Symposium. Lisbon: Instituto Superior Técnico, Departamento de Engenharia Civil, Arquitetura e Georrecursos, Portugal.
19		UrbanMetrics	2017	Lima, F., Montenegro, N., Paraizo, R. and Kós, J., 2017, July. Urbanmetrics: An Algorithmic-(Para) Metric Methodology for Analysis and Optimization of Urban Configurations. In International Conference on Computers in Urban Planning and Urban Management (pp. 47-64). Springer, Cham.
20		Urbano	2018	Dogan, Timur, Samitha Samaranayake, and Nikhil Saraf. "Urbano: a new tool to promote mobility-aware urban design, active transportation modeling and access analysis for amenities and public transport." In Proceedings of the Symposium on Simulation for Architecture and

				Urban Design, p. 28. Society for Computer Simulation International, 2018.
21		Reach analysis algorithms	2019	Feng, C., & Zhang, W. (2019). Algorithms for the parametric analysis of metric, directional, and intersection reach. Environment and Planning B: Urban Analytics and City Science, 46(8): 1422–1438.
22	MTM	Mobility Topography Model	2017	Trattner, Z., Chronis, A. and Muñoz, A., 2017, May. The mobility topography model for substantializing and projecting transportation in cities. In Proceedings of the Symposium on Simulation for Architecture and Urban Design (p. 33). Society for Computer Simulation International.
23	MASTIC	Model of Action Space in Time Intervals and Clusters	2002	Dijst, M., de Jong, T. and van Eck, J. R. (2002) 'Opportunities for transport mode change: An exploration of a disaggregated approach', Environment and Planning B: Planning and Design, 29(3), pp. 413–430. doi: 10.1068/b12811.
24		Space-time accessibility measures: A geocomputational algorithm	2003	Kim, H. M. and Kwan, M. P. (2003) 'Space-time accessibility measures: A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration', Journal of Geographical Systems, 5(1), pp. 71–91. doi: 10.1007/s101090300104.
25		People-based joint accessibility	2007	Neutens, T., Witlox, F., Van De Weghe, N. and De Maeyer, P.H., 2007. Space–time opportunities for multiple agents: a constraint-based approach. International Journal of Geographical Information Science, 21(10), pp.1061-1076.
26	MAMPAM	Multi-Activity Multi-Person Accessibility Measure	2009	Soo (Kum Lin, Joyce, Kum Lin, Joyce), 2009. Towards a Multi-activity Multi-person Accessibility Measure. Faculty of Geosciences, Utrecht University.
27	SAL	Structural Accessibility Layer (SAL)	2010	Silva, C. and Pinho, P., 2010. The Structural Accessibility Layer (SAL): revealing how urban structure constrains travel choice. Environment and Planning A, 42(11), pp.2735-2752.
28	MMUN	Multimodal urban network (MMUN)	2014	Gil, J., 2014. Analyzing the configuration of multimodal urban networks. Geographical Analysis, 46(4), pp.368-391.

Table 8. List of 28 analytical constructs found in literature (six different types are identified and colour coded),

2.3.7 Findings

Six different types of computational analytical constructs can be identified:

1. **Transport demand model** that has an emphasis on **road-based traffic simulation** (e.g. SUMO and MATSIM)
2. **Macro-scale system dynamics** that contain an **equation-based transport model** within a larger Land use Transport Integrated model (e.g. MARS)
3. **Travel demand model** developed to be embedded within a Land use Transport Integrated model with an emphasis in **disaggregated activity-based representation of people** (e.g. LUTDMM, FEATHERS)
4. Models that focus on **activity pattern generation** associated to **activity-based approaches** to travel demand modelling and analysis (e.g. ALBATROSS)
5. Models to compute different variations of **metrics of urban characteristics** related to urban movements that are spatially varied (e.g. UNA)
6. Models to compute different variations of **accessibility** metrics or indicator that are spatially varied (e.g. MASTIC, SAL)

2.3.8 Inputs to analytical constructs

2.3.8.1 Space-related inputs

Most analytical constructs (type 1,3,4,5 and 6) include transport networks as space related inputs, but not all of them use a detailed representation of a transport network. It is a common requirement for a transport network to be described computationally as a network graph for network analysis or routing algorithms to function. There are also differences in emphasis on the types of transport networks included. Type 1 has an emphasis on road networks, type 5 has an emphasis on street networks.

Analytical constructs that do not include detailed transport networks conceptualise space as a Transport analysis zone (TAZ) (type 2 and 3) or as spatial variables (type 4) or as locations of opportunities (type 6).

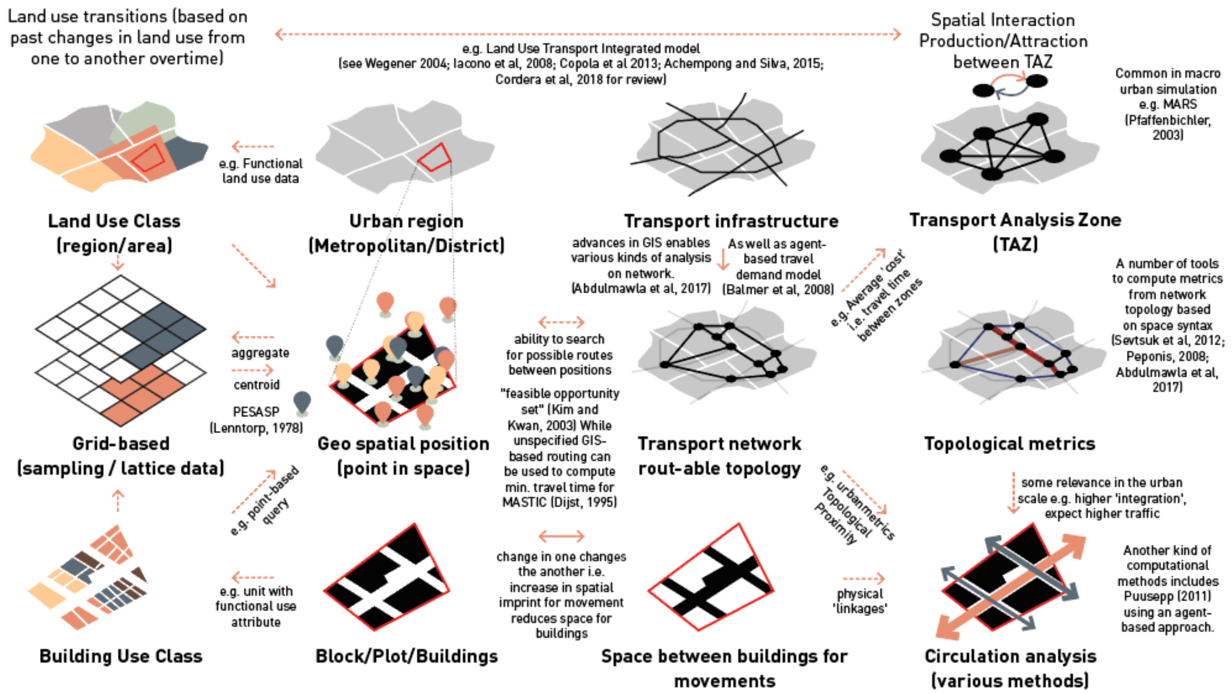

Figure 12 multiple ways in which the transport as a connection between physical space is conceptualied

2.3.8.2 People-related inputs

There are limited but relevant people-related inputs related to type 1 with a focus on road traffic simulation and type 2 with a focus on macro scale urban system. Type 1 related inputs include an origin-destination matrix and activity plan (schedule) (see section 2.2.3 for an introduction to the two different approaches pg76-83). Type 2 with a macro scale system dynamics model consists of a common mode choice model within a four-step model (see section 2.2.3.1 for background context on four step model pg77).

Type 4 focuses on activity pattern generation consist of two formulations:
(1) econometric models that frame the choice of activity as a utility-based choice question (see section 2.2.2.3 on indiviudal travel behaviour pg74)
(2) from the analysis of empirical data, for example in ALBATROSS, mode choice is derived from the analysis of sequential data of observed activity sequence using transitional probability (see section 2.2.3.2 for background on activity-based approaches pg79).

Type 5 mostly consists of the formulation of metrics of urban characteristics, including the transport network related to certain qualities through interpretations or arguments supported by related research e.g. correlation between metrics and a certain outcome (Carr, Dunsiger and Marcus, 2011).

Type 6 consists of the formulation of metrics that reflect the facilitating and constraining property of the physical geographical functional space and transport network on the possibilities for people to reach or access locations of opportunities or as areas that can be reached within a defined threshold of distance or time. There are specific examples that enable the investigations at an individual or group level, for example, the concept of action space, a joint potential path area between two people.

2.3.9 Outputs from analytical constructs

Three groups can be identified when the analytical constructs are grouped by the **type of model outputs**. **Group 1** (analytical constructs type 1,2 and 3), produces a quantified amount of transport activities associated to a spatial unit. **Group 2** (analytical constructs type 4) consists of models aimed at the generation of activity patterns of individual decision unit given the socio-economical context or individual preferences. **Group 3** (analytical constructs type 5,6) produces spatially varied metric or indicator that is associated to urban movement derived from spatial features such as transport network and physical locations.

Inputs		**Outputs**	**Related type of analytical constructs**
Space-related	**People-related**		
Transport network		**Location-based accessibility**	6. Accessibility
		Accessibility as indicator of certain qualities	
Road network			1. Transport demand model
Street network		**Metric of urban characteristics as indicator of certain qualities**	5. Metrics of urban characteristics
Transport analysis zone	**Origin-Destination matrix**	**Quantified amount of transport activities**	1. Transport demand model 2. Macro-scale transport model
	Activity plan		3. Travel demand model
Spatial variables (indirect)	Econometric (parameters in utility function)	**Activity pattern**	4. Activity pattern generation
	Activity sequences for transitional probability		4. Activity pattern generation
		Person-based accessibility	
Locations of opportunities	Individual activity programme (sequence of activity over a day)	Action space as a person-based accessibility indicator	6. Accessibility

	Single person in space-time	Space-time prisms/Potential path area	6. Accessibility
	Two people in space-time	Potential Interaction area	6. Accessibility

Table 9: Summary of identified inputs and outputs from analytical constructs

2.3.10 Discussions: state-of-the-art computational analytical constructs

City design involves the consideration of alternative urban conditions to the existing conditions. Alternative urban conditions are, by definition, conditions that do not exist or yet to exist in the real world. Although travel activities can be monitored and tracked through a data collection process and analysed after the fact, potential travel activities are by definition yet to occur and cannot be directly observed. The combination of these two meant that the analysis of potential travel activities under a certain urban condition requires theoretical constructs that draw the relations between urban conditions and potential travel activities.

Computation-enabled analytical constructs include the operationalisations of underlying theoretical constructs. In other words, for a computer program to operate, the input must be transformed to output in a mathematical or a logical way. What can be known about an alternative urban condition depends on the theoretical connection between the inputs and outputs and how it is justified.

The state-of-the-art computational analytical constructs are therefore not defined by the functionality of the analytical constructs but the underlying analytical approach and its corresponding justifications to draw the connection between the inputs and its outputs of the analytical constructs. This relationship between inputs and outputs are covered by the literature review in section 2.2 which includes the theoretical knowledge and considerations in fundamental-oriented research. The next section will synthase and further discuss the connections between section 2.2 and section 2.3 towards the overall aim of this study.

2.4 Synthesis

The overall study aims to develop a computational analytical construct to facilitate scenario modelling and diagnostic assessment of alternative urban conditions towards sustainable transport systems and to support sustainable travel activities.

As identified in section 2.3.10 pg98, there is a need to clarify the theoretical knowledge and considerations needed to support the development of an appropriate computational analytical construct for such purpose.

This synthesis is structured in three sections:
1. To understand the position of computational analytical construct within the multiple perspectives relating travel activities and urban conditions in a fundamental-applied continuum considering both literature review section 2.2 and 2.3.
2. To identify known analytical approaches with an emphasis on the underlying theoretical knowledge and considerations.
3. To relate known analytical approaches to notions of transport/travel-related sustainability towards sustainable transport systems and to support sustainable travel activities.

This synthesis concludes with an identification of an analytical approach for further exploration and the research gaps towards the aim of the overall study.

2.4.1 Position of analytical constructs in a fundamental-applied continuum

In a planning research context, “applied research” is “driven by practical aims and is conducted in practice for purposes of offering practical solutions to concrete problems”, “basic research” is “driven by theoretical aims and is conducted in academia for purposes of advancing fundamental knowledge about planning and the world that planning deals with” (Barry, 2014, p. 62)

Four positions are identified ordered by two ends of a continuum of applied research and fundamental research – from the point where analytical construct is an instantiation for application more related to applied research, to the point where explanations in the fundamental phenomenon of interest are the subject of research studied through an analytical construct, normally found in empirical studies related to fundamental research.

Four broad motivations are 1) to provide information, 2) to understand, 3) to investigate, and 4) to explain or predict. The first two are more aligned with literature reviewed and discussed in the second section 2.3 pg89-98, and the latter two more aligned with to literature reviewed in the first section 2.2 pg71-88.

1) Decision Support Systems - Analytical constructs for someone else, other than the researcher, to understand the implications of spatial reconfigurations on potential travel activities in alternative urban scenarios

Analytical constructs developed by researchers, usually as a tool, to provide an understanding of the implications of changes made to an urban system on likely future urban movements that are relevant towards defined evaluative goals such as environmental sustainability. The analytical constructs are aimed at supporting design/decision-making processes for the target users either by providing insights or for direct operation and use by the target users. The role of analytical construct is to provide insight for target users as an instantiation for application in a specific problem.

In transport planning practice, models are built for specific geographical context, usually with a focus on road traffic for transport project appraisal and transport-related project design. Currently, in the UK, building developments that "generate significant amounts of transport movement" under NPPF 32 require supporting transport assessment and a technical traffic impact assessment (TIA). This type of model is used in traffic impact assessment.

In academic research, analytical constructs are related to an area of research in planning/decision support system (PSS/DSS) (van Leeuwan and Timmermans, 2006; Geertman, 2014), the concept of "sketch planning" in transport-related studies (Difiglio and Reed, 1975) and planning (Harris, 2001) including studies in the use of transport models (an analytical construct) in sketch planning approach (Williams, 2010)**.** On the more urban spatial design side, examples include Urbanmetrics (Lima *et al.*, 2017), Urban Network Analysis toolbox (Sevtsuk and Mekonnen, 2012), and Urbano (Saraf, Dogan and Samaranayake, 2018).

2) Model for scenario analysis - Analytical constructs to understand the implications of the potential travel activities from spatial reconfigurations in alternative urban scenarios

Analytical constructs developed and used by researchers to understand the implications on the potential travel activities from reconfigurations of urban system usually referred to as "alternative scenarios" (Chatterjee and Gordon, 2006) or "alternative urban configurations" (Cajot *et al.*, 2017) that do not currently exist in the real world. The role of an analytical construct is to provide insight for the researcher as an instantiation for analysis. At the same time, there are known research activities that aim at developing analytical constructs for the purpose of instantiation for analysis where models and methods are central to the studies.

Related research includes studies that adopt a scenario analysis approach to urban situations. This type of study involves the development of a **model for specific geographical context** either by using a modelling system (such as Matsim or Urbansim) or own development (Matsim and Urbanism were developed by researchers). Scenario analysis typically includes a baseline model that is constructed with calibration and sometimes validated against data of the specific context. A set of defined alternative design/policy scenarios is then simulated and compared to the baseline model for the evaluation of possible implications of alternative options (Waddell and Ulfarsson, 2004).

There is a difference between the development of a model and a method (see table 2.2.1) and the instantiation for analysis in a specific context (see table 2.2.2). One example is Phahhenbichler's development of MARS (Metropolitan Activity Relocation Simulator) as a simulation system from his PhD thesis (Pfaffenbichler, 2003). The thesis contains a case study demonstration of effectiveness in a specific context but without emphasising the use of the analytical construct for analysis in a specific context. Alonso and Wang (2017) is an example of a study that adopts the use of MARS as an analytical construct for analysis in a specific context to understand the likely effect of different policy measures in Madrid.

3) Model of urban system - Analytical constructs to investigate potential travel activities in an existing context based on the underlying theories towards a model of future travel activities

Analytical constructs as models developed by researchers aim towards a model of future urban movements based on known conditions and relationships. If they are developed as scientific models, typically, model assumptions are calibrated and validated with historical data by backtesting. The detail calibrated and validated procedures differ under different model formulation. For example, see the calibration and validation procedure in SLEUTH land use change model (Clarke, Hoppen and Gaydos, 1997; Silva and Clarke, 2002).

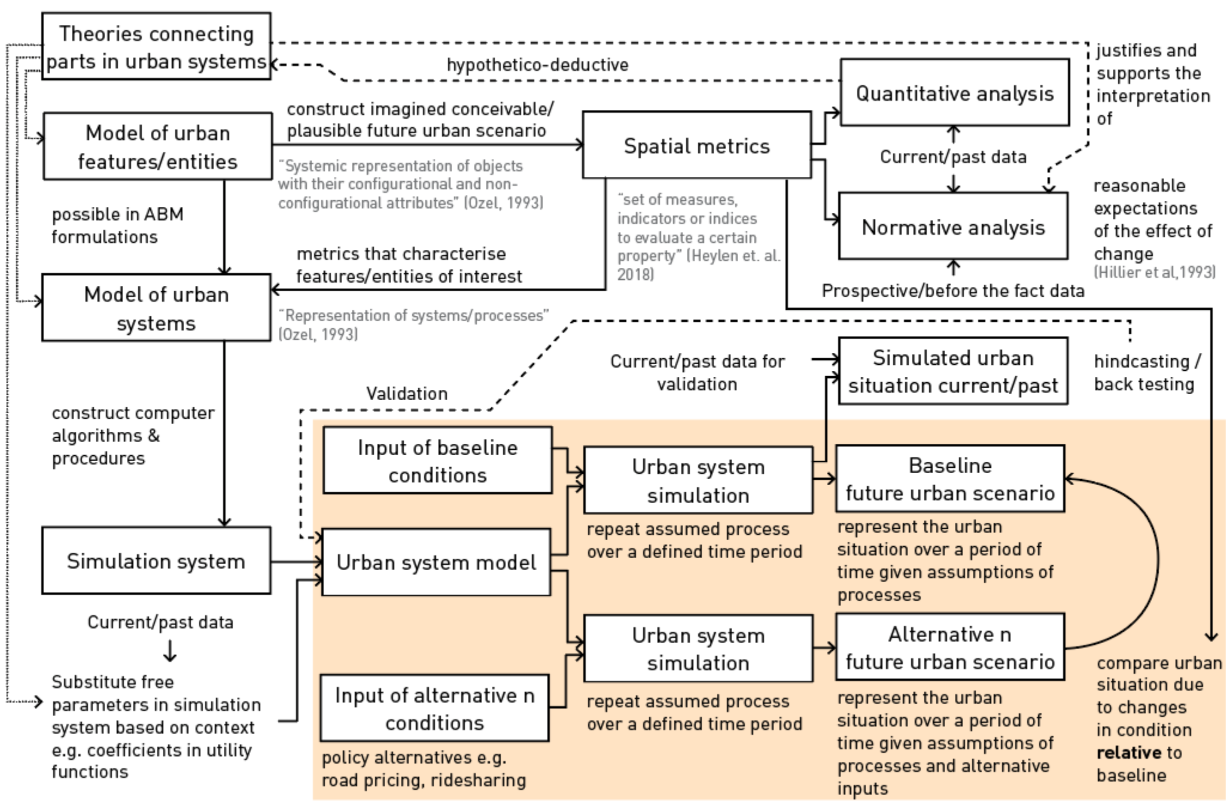

Figure 13 Model development and reasoning processes

Research activities aim at developing analytical constructs as a model for the purpose of instantiation for analysis where models and methods are central to the studies. The role of an analytical construct as a scientific model is to provide an instrument for the researcher as an instantiation for analysis, where hypothetical-deductive approach is used to test the model as an embodiment of theory against empirical data (Batty, 2009).

In academic literature, models are often **developed as modelling frameworks** (**simulation systems**). They can be based on a different **approach** that results in a different structure, data requirements, and parameters that are designed to be sensitive towards certain types of problems or policy goals. For example, DRACULA (Dynamic Route Assignment Combining User Learning and microsimulAtion) and SATURN (Simulation and Assignment of Traffic to Urban Road Network) developed at the University of Leeds for highway assignment and traffic simulation respectively. More recent modelling frameworks include ALBATROSS (A Learning Based Transportation Oriented Simulation System) for travel demand analysis and MATSIM (Multi-Agent Transport Simulation) originally tailored towards traffic modelling, but is since increasingly used for other types of questions. This type of model or approach used is sometimes incorporated into or developed as a **part of larger modelling framework** in Land Use Transport Integrated models for processes involving transport systems. MARS is an example of a macro level modelling framework. For a recent comprehensive review and description of the state of Land Use Transport Integrated models see Acheampong and Silva (Acheampong and Silva, 2015).

4) For empirical studies - Analytical constructs to study patterns/behaviour related to movements of people in urban areas in an existing context from past data

Analytical constructs for the analysis of a phenomenon are aligned with quantitative empirical research methods that employs well known statistical methods to study the topic of movements of people in urban areas using past datasets. These methods range from regression analysis (Aditjandra, Mulley and Nelson, 2009) to more advanced techniques such as Structural Equation Modelling (SEM) (Golop, 2003).

There is a wide variety of research under the topic of movements of people in urban areas. Two main types of studies can be identified: (1) observed travel patterns in relation to other factors and (2) choice behaviour studies.

Another use of analytical constructs related to empirical studies is the analytical construct as a data collection method. An example is GABRIEL (Gis Activity-Based tRavel sImuLator) (Kwan and Casas, 2006), where the analytical construct consists of GIS combined with a stated preference survey.

Research motivation	**Relationship between analytical construct and people involved**	**Purpose of analytical construct (example)**	**Research outputs (based on concepts from IS)**
1. to provide an understanding of the implications of spatial reconfigurations on potential travel activities in alternative urban scenarios	Analytical construct developed by researchers 1.1.1 Researcher uses the analytical construct to provide insights for target users or 1.1.2 For direct operation and use by target users	1.2.1 to provide an understanding of the implications of changes made to an urban system on likely future urban movements that are relevant towards defined evaluative goals such as environmental sustainability and 1.2.2 to support design/ decision-making processes for the target users	Justified use of model and method **Analytical construct as instantiation for application**
2. to understand the implications on the likely amount of travel activities from spatial reconfigurations in alternative urban scenarios	2.1.1 Analytical construct developed by researchers	2.2.1 a method to understand the implications of the likely outcomes in “alternative scenarios” that does not current exist in the real world.	Define use of theoretical construct **Develop computational construct** Justified use of theories **Analytical construct developed as Model and method** Instantiation for analysis (demonstration)
	2.1.2 used by researchers	2.2.2 to understand the implications of the likely outcomes in “alternative scenarios” that does not current exist in the real world.	Justified use of model and method **Instantiation for analysis in a specific setting**
3. to investigate potential travel activities in an existing context based on the underlying theory towards a model of future potential travel activities	3.1.1 Analytical construct developed and used by researcher	3.2.1 as a method to investigate/test hypothesis on movements of people in an urban area based on known conditions and relationships	Define use of theoretical construct **Develop computational construct** Justified use of theories **Analytical construct developed as Model and method** Instantiation for analysis (demonstration)
4. to study a topic related to movement of people in an existing urban context from past data	4.1.1 Analytical construct typically involves adopted statistical methods and used by researchers	4.2.1 to study patterns/behaviour related to movements of people in an urban area using empirical data	Define or justify theoretical constructs Theory (deductive testing of theory or inductive generalisation for theory) Adopt analytical construct as model and method **Analytical construct as instantiation for analysis in a specific setting**

Table 10: Overview of the four general ways in which analytical constructs is used in research related to potential travel activities from applied research (top) to fundamental research (bottom) (author’s own)

2.4.2 Fundamental-applied research approaches in the analysis of implications on potential travel activities in alternative urban conditions

Following the previous discussion (pg98) on the justification required for the connection between the inputs and its outputs of the analytical constructs reviewed in section 2.3. **Three main types of fundamental-applied research approach** can be identified where the connection between the inputs and its outputs are distinct in relation to concepts for transport and travel analysis reviewed in section 2.2.

1. **Metrics of urban characteristics**
2. **Model of urban systems**
3. **Space-time accessibility**

2.4.2.1 Metrics of urban characteristics

Metrics of urban characteristics-interpretation/correlation-data

There are analytical constructs that are solely associated with **space with the absence of people related inputs** and require interpretation or other research in order to relate to movements of people. The general basic research approach within this type is to develop a metric that characterises urban areas or transport networks and proceed to correlate with observable data from phenomena of interest such as network flow (Gil, 2014). The analytical constructs focus on methods to bridge between a spatial description of urban design and the conversion from geometries to metrics with knowledge contributions towards design processes and the applied research end of the continuum. (see section 2.2.2.1 pg72)

The analytical constructs that include an understanding of potential travel activities in urban areas with the inclusion of people-related inputs and space-related inputs result in outputs in two different kinds of analytical constructs. The first kind of analytical construct results in **quantified amount of transport activities**. The second results in **abstract constructs** such as accessibility measures that associate space and the movement of individuals or groups through spatial constraints and opportunities. Accessibility can be conceptualised in terms of location-based and person-based as discussed previously in section 2.2.4 pg83-88, accessibility measures as metrics of urban characteristics refers to location-based accessibility.

2.4.2.2 Model of urban systems

Model of urban systems-travel behaviour-data

Analytical constructs result in a **quantified amount of transport activities** adopts a scientific model building approach and relates to alternative urban scenarios through a simulation approach. The general research approach within these types is to develop an analytical construct as a model of an urban system and test it against past data on the amount of transport activities towards a predictive model (see section 2.2.3 pg77 and section 2.4.1 pg101). There are commonly stated intentions for the model to be used towards policy scenario analysis, to ask “what if” questions for transport-related proposed plans and policy actions (Arentze and Timmermans, 2000; Xu, Taylor and Hamnett, 2005).

2.4.2.3 Space time approaches
Space-time approaches-person based accessibility-activity programme

Analytical constructs result in abstract constructs which requires interpretations. The abstract constructs associate space and the movement of individuals or groups through temporal and spatial constraints and opportunities provides a unique perspective to understand movements of people from an individual or group point of view taking into account different constraints from the wider context. For example, Neutens et al development of the abstract construct of Potential Interaction Area (Neutens *et al.*, 2008).

The literature reviewed in this study includes the different formulations of abstract constructs and related metrics that has its root in time geography. In brief, this type of abstract constructs delineates the possible space and time where a non-living or living entity can be physically present based on the physical and temporal limitations of physical movements typically associate to the commitment/needs for a non-living or living entity to be physically located in different space and time.

There are two forms of studies found in this review in section 2.3 pg89-98. First, the development of constructs. Second, in the form of analytical constructs to understand the implications of changes in alternative urban scenarios though a combination of empirical trip diaries of residents and simulation approach (Dijst, de Jong and van Eck, 2002) supported by earlier development of constructs of MASTIC (Dijst, 1995). MASTIC and an earlier space time model of PESASP (Lenntorp, 1976) was discussed earlier (see section 2.2.3.2 pg80) in this chapter under activity-based travel analysis. Besides activity-based travel analysis, the space time models of PEASASP and MASTIC has also informed the formulations of space time accessibility introduced earlier in this chapter under accessibility.

The connection to concepts in transport and travel analysis can be found under an activity-based approach (section 2.2.3.2 pg 79) and at a more fundamental level in terms of activity patterns of indiviudals (section 2.2.2.4 pg75).

2.4.3 Relationships between analytical constructs and different notions of transport/travel-related sustainability

2.4.3.1 Overview
In the wider context, there are three broad notions of sustainability related to movement of people in urban areas. Although there are multiple definitions and description of different notions inclusive of multiple emphasis, specific notions related to what can be known from analytical constructs under different notions is discussed here for simplicity. A more transport-oriented view of sustainable transport with notions of **low GHG emissions transport activities** (Richardson, 2005) and **multiple transport options**

(Litman, 2017) and more people-oriented views of sustainable mobility and sustainable accessibility, the former with notions of enhancing **space and experiences for non-motorised travel modes** as well as considerations of all modes of transport (Banister, 2008) and the latter with includes different notions of **accessibility** and considerations of constant **societal changes** (Couclelis, 2000).

Notions in transport/travel-related sustainability	Type of analytical constructs (section 2.3)	Fundamental-applied research approaches (section 2.4.2)
Multiple transport/travel modes	1. Transport demand model 2. Macro-scale transport model 3. Travel demand model 4. Activity pattern generation	Model of urban systems
	5. Metrics of urban characteristics 6. Accessibility	Metrics of urban characteristics
	6. Accessibility	Space-time approach (person-based accessibility)
Transport activities	1. Transport demand model 2. Macro-scale transport model 3. Travel demand model	Model of urban systems
Space and experience for non-motorised travel modes	5. Metrics of urban characteristics 6. Accessibility	Metrics of urban characteristics
	6. Accessibility	Space-time approach (person-based accessibility)
Different notions of accessibility	6. Accessibility	Metrics of urban characteristics (location-based accessibility) Space-time approach (person-based accessibility)
Societal changes	3. Travel demand model 4. Activity pattern generation	Model of urban systems
	6. Accessibility	Space-time approach (person-based accessibility)
Public participation	6. Accessibility	Metrics of urban characteristics (location-based accessibility) Space-time approach (person-based accessibility)

Table 11: Summary of possible relationships between analytical constructs, research approaches and different notions of transport/travel-related sustainability

All identified types of analytical constructs include considerations of multiple transport/travel modes to varying degree. Transport demand model, macro-scale transport model and travel demand model (with activity pattern generation) relies on a mode choice model (see section 2.2.3.1 on four step models pg77). This meant that the mode choice that could be studied is dependent on the formulation of the mode choice model (MCM). A typical basic example of a utility-based mode choice model (Bowman and Ben-akiva, 1996) contains a formulation of a utility function with travel time and cost. In operation, it results in the probability of an individual choosing a particular mode when all alternative travel options are considered for a trip between an origin and destination. Metrics of urban characteristics has an emphasis on non-motorised modes especially for pedestrian movements, the connection between this type of analytical construct and public transport is often limited to principles such as proximity to stops or station locations. Analytical constructs that focus on accessibility tends to compare different modes under different circumstances. For example, SAL produces a comparative index for different travel modes at different location based on the diversity of activity. Dijst et. al. study using MASTIC investigates the opportunity of mode shift to public transport in an urban context.

The estimation of transport activities for an alternative urban scenario is limited to transport demand model, macro-scale transport model and travel demand model as they produce a quantified amount of transport activities as an output.
Space and experience for non-motorised travel modes is mainly a topic for design but it can be related to metrics of urban characteristics and accessibility. In particular, the ones developed for pedestrian movements and measures of walkability. Accessibility reviewed in this study is not directly related to this notion explicitly, but examples has shown that accessibility can be understood and compared for different travel modes. Urban design has some ability to modify the way in which different travel modes operates in an urban context. For example, through designs principles such as filtered permeability (Melia, 2012).

There are different notions of accessibility and this review of recent analytical constructs is not an exhaustive that captures the different notions (see section 2.2.4 for a more detail description and discussion on the notion of accessibility pg83-88). However, this review identifies two distinct approaches to accessibility (1) location-based and (2) person-based. This distinction is relevant to the discussion of sustainable mobility and sustainable accessibility as there is a tendency under these two notions towards a more people-focus approach.

Societal changes related to transport has long been a topic in urban studies in the wider context. Analytical constructs such as travel demand model and activity generation models contain certain formulations that are able to investigate certain types of changes especially intended for transport demand related policies. For example, ridesharing, increase in teleworking are scenarios analysis known to be built-in within some of the analytical constructs. However, there are limitations in analytical constructs when constructed following a deductive scientific methods where the data requirements for calibration and validation is an issue especially for models that are disaggregated that attempts to represent “activity-travel decision processes” (Acheampong and Silva, 2015). There are, however, exploratory approaches that attempts to investigate "potential impacts of evolving technologies and changing circumstances" (Trattner, Chronis and Muñoz, 2017) and analytical constructs such as MASTIC (Dijst, de Jong and van Eck, 2002) that takes into account finer details of possible changes both in the environment and the way in which people modifies their everyday activity schedules.

Bertolini et. al. (Bertolini, le Clercq and Kapoen, 2005) has demonstrated an approach to involve public participation in such conversation through the use of various accessibility measures in order to co-create and identify the context-dependant value embedded in the notion of sustainability and critically assess the different possibilities in changes of the urban environment through a collaborative "plan-making process" with discussions assisted by accessibility measures.

2.4.3.2 Analytical approaches and transport and travel-related sustainability

Three broad analytical approaches can be identified relating different aspects of transport and travel-related sustainability.

1) **Metrics of urban characteristics** to indicate probable outcomes

This approach provides useful insights specific to pedestrian and vehicular movement patterns through probable patterns of people movement given an urban condition contributes to the design process for "walkability" and "street as a space" both of which are related to the **people-focus aspects of sustainable mobility** but they are limited in the study of passenger transport as a travel mode, which is not useful for the focus in this study for the comparison of travel modes in alternative urban conditions.

2) **Transport models** (part of models of urban systems) to estimate probable transport/travel activities

This approach provides useful insights in the **estimation of the amount of transport activities**. Estimated amount of transport activities by different travel modes contributes to the process of estimating amount of GHG emissions associated to transport activities. There are known procedures to estimate the amount of transport activities by different travel modes. The process of **estimating the modal split** essential to separate the estimation of the amount of transport activities by different travel modes depends on formulation of the estimation process. The process typically includes (1) travel time and cost and (2) the formulation of a "choice set" as a set of alternatives supported by different travel modes between an origin and destination pair. However, there are no standard specifications in the formulation of "choice set" between opportunities, which is complimentary but different from the focus of this research in the comparison of travel modes in alternative urban conditions.

3) **Accessibility-based approaches** to delimit the possibilities of movement and access to opportunities

Accessibility in this context refers to the ease of access to opportunities distributed across space, and in some formulation, time. Accessibility-based approaches enables the analysis of existing and alternative urban conditions by delimiting the possibilities of movement and the access to opportunities by different travel modes. The distribution of accessibility in alternative urban conditions meant that the set of alternatives to travel between opportunities supported by different travel modes can be assessed. This contributes to the understanding of the availability of alternative travel modes across a geographical area to support sustainable travel activities.

Out of all three approaches, accessibility-based approaches are closely aligned with the research motivation in supporting scenario analysis for the wider problem of transport integrated city design to support sustainable travel activities (see section 1.6 pg62-66).

Different conceptualisations of accessibility have been reviewed in an earlier section 2.2.4 pg83-88, with the distinction between location-based and person-based accessibility. In the context of fundamental-applied research approaches (section 2.4.2 pg104), location-based accessibility relates to metrics of urban characteristics and person-based accessibility relates to space-time approaches (section 2.4.2.3 pg105).

2.4.4 Summary of synthesis

The first section of the literature review identifies approaches and conceptualisations in fundamental research for transport and travel analysis in three parts. The first part begins with an overview to identify conceptualisations related to fundamental research in transport and travel-related analysis. The overview of travel behaviour literature identifies study of past activities and the possibilities to estimate future activities reflecting two different scales of thoughts. One scale draws relationships between built environmnet characteristics to outcomes of travel activities and the other conceptualises individual behaviour resulting in outcomes of travel activities. This led to the second part with a further investigation into dominant modelling approaches in transport and travel analysis, namely a four-step modelling approach and an activity-based approach. The third part elaborates the concept of accessibility that conceptually relates the built environment to transport systems.

The second section of the literature review focuses on ex-ante (before the fact) analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions from recent literature with specific emphasis on what can be modified as inputs and the outputs from the analytical constructs. This resulted in the identification of six types of computational analytical constructs – 1) transport demand model, 2) macro-scale system dynamics, 3) travel demand model, 4) activity pattern generation, 5) metrics of urban characteristics, and 6) accessibility.

The particular focus on analytical constructs for scenario analysis (section 2.3) in this study raises the question of what can be known from alternative urban conditions – covered in the section 2.2. Section 2.4.2 relates the concepts from section 2.2 to section 2.3 and identifies three types of **fundamental-applied research approaches**
1) metrics of urban characteristics, 2) model of urban systems, and 3) space-time approaches with theoretical and methodological connection between fundamental

research and applied research for the analysis of implications to potential travel activities in alternative urban conditions.

The section 2.4.3 identifies **three analytical approaches** for scenario modelling and analysis (section 2.4.3.2) to anticipate implications of alternative urban conditions on travel activities **towards transport/travel-related sustainability**: 1) metrics of urban characteristics 2) transport model, and 3) accessibility-based approaches. Each analytical approach relates to different **fundamental-applied research approaches**.

2.5 Conclusions and research gaps

Three broad types of research from fundamental to applied research relevant to transport/travel-related sustainability in alternative urban conditions is identified through the combination of conceptualisations of transport and travel activities from the first section (section 2.2) and the approaches to ex-ante analysis of alternative urban conditions in the second section of the literature review (section 2.3).

1. **Metrics of urban characteristics**-interpretation-correlation-data: metrics of urban characteristics for alternative urban scenarios is supported by research in observable travel activities or other phenomena of interest to defined metrics.
2. **Model of urban systems**-travel behaviour-data: Model of urban systems for alternative urban scenarios produces quantified amount of transport activities given different urban socio-economic conditions is supported by empirical research and model-based research in travel behaviour
3. **Space-time approaches**-person based accessibility-activity programme: Space-time approach to alternative urban scenarios provides an exploratory model to understand the logical implications towards changes, supported by micro scale data collection of trip diaries.

There is a lack of an adequate computational analytical framework that considers new urban developments and transport services in the analysis of alternative urban scenarios. In particular, in terms of the comparison of travel modes in combination of new urban developments. A space-time analytical approach theoretically supports the analysis of travel modes in alternative urban conditions. Previous examples of space-time models have demonstrated the possibilities for the use of a space-time analytical approach for the comparison of travel modes. However, the development of model and methods for ex-ante analysis of alternative urban conditions is underdeveloped.

There is a dominance of metric of urban characteristics and design principles informed analytical constructs related to transport-integrated city design including density, diversity and space syntax measures. As mentioned previously in 2.4.2 pg105, the analytical approach is limited in the study of passenger transport. Passenger transport is an important issue in the wider context of a sustainable transport system identified in this study.

There are two ways to relate model of urban systems and transport/travel-related sustainability. The first is the estimation of the amount of transport activities and the second estimation of modal split. The estimation of modal split is the most relevant to this study with a focus on passenger transport. However, from the background context of transport and travel analysis, the best possible method to estimate modal split is to date a mode choice model. As mentioned earlier in 2.4.2 pg105 a mode choice model while requires a 'choice set' of alternatives, the economic orientation of current mode choice models has strong theoretical underpinnings in the economic constraints (McFadden, 1974; Ben-Akiva and Lerman, 1985) the spatial and temporal constraints however has been augmented by space time approaches as the delineation of "feasible choice set" (Chen and Kwan, 2012) as well as the use of space time prism in conjunction to a utility based approach (Kitamura, 1997). In a model of urban systems context, a weakness in typical method to estimate modal split has been filled by the strength of space time approaches.

Accessibility as a concept and as a metric otherwise appears to possess the greatest potential connection with different notions of transport/travel-related sustainability as well as across planning (e.g. transport models), design (e.g. metrics of urban characteristics) and policy (e.g. models of urban systems). Both as a high-level aim from planning for increased mobility to reasonable accessibility. It also has the potential as an analytical construct to assist with stakeholder/public participation towards sustainable accessibility. While the researcher's choice of a particular accessibility measure for the purpose of sustainable accessibility has been explored in recent work (Silva and Pinho, 2010) it remains an open question (Bertolini, le Clercq and Kapoen, 2005).

Accessibility-based approaches are closely aligned with the research motivation in supporting scenario analysis for the wider problem of transport integrated city design to support sustainable travel activities (see section 1.6 pg62-66). In particular, the space-time approach (section 2.4.2.3) to accessibility (section 2.4.3.2) with the ability to study a combination of future built environment and time-sensitive transport services as an option amongst other personal travel modes such as driving, walking and cycling.

Space time approaches have been applied to aid an understanding of sustainable travel activities. Lenntorp's PESASP is a space time model developed (Lenntorp, 1976) and applied in studies of travel modes possibilities in the city of Karlstad (Lenntorp, 1978) and the city of Orebro (Lenntorp, 1979). Dijst's MASTIC (Dijst, 1995) was developed in 1995 and subsequently applied in the study of mode change opportunities (Dijst, de Jong and van Eck, 2002) and explorative simulation study of spatial configuration in the city of Zoetemeer (Ritsema van Eck, Burghouwt and Dijst, 2005).

There is a connection between PESASP, MASTIC to both an activity-based travel analysis approaches and a space time approach to accessibility. However, there is a difference between PESASP, MASTIC and the further developments found under the two branches of study. The difference is that PESASP and MASTIC has demonstrated the potential of their application to investigate alternative urban conditions evident in the study of travel modes possibilities in the city of Karlstad (Lenntorp, 1978) and the explorative simulation study spatial configuration in the city of Zoetemeer (Ritsema van Eck, Burghouwt and Dijst, 2005).

Although PESASP and MASTIC has demonstrated the potential as an underlying space time model for further investigations in alternative urban conditions, the space time model itself is relatively underdeveloped compared with similar developments in space time approach to accessibility for existing urban conditions. In particular with the transport network and the computation of travel time that limits the reachable opportunities.

Example of the latter are the formulation of space time accessibility as a measure (Villoria, 1989), the introduction of transport network as network-time prism (Miller, 1991), the integration with GIS (Kwan and Hong, 1998), the introduction of joint accessibility (Neutens *et al.*, 2007) and the introduction of space time constructs as a plugin in a commercial GIS (Charleux, 2015).

A core part of the underlying space time model has been advanced over time in this closely related area of study, more specifically in the introduction of transport network (Miller, 1991) and making use of GIS network analyst (Charleux, 2015). There is a general trend in the improving the transport network representation and by extension the computation of travel time across the transport network – a core procedure in a space time approach that is sensitive to space and time. However, the advancement of space time model under these study area lacks the simulative quality essential for prospective alternative urban conditions observed in studies conducted using PESASP and MASTIC.

2.5.1 Research gaps in relation to methodological development as constructive research

1. Space time models for alternative urban conditions

There is an established line of research in space-time models to anticipate the possibilities of movement in urban conditions with multiple possibilities of human actions facilitated and constrained by the physical space, use of space, transport infrastructure and transport services. There are limitations in the formulations that requires further development which will be explained in detail later in the document. In particular, “space-time model” aimed at alternative urban conditions.

2. Develop stand-alone procedures for space time models

Space-time accessibility relies on analytical constructs that is highly specialised with “increasingly complex algorithms” (Kwan and Hong, 1998; Kwan, 2004a; Neutens, Schwanen and Witlox, 2011). Recent work on space-time accessibility typically develops the analytical construct with an emphasis for empirical studies purposes. They are usually developed on top of existing commercial Geographical Information System (GIS) packages (Charleux, 2015) that is difficult to specify the inputs of alternative urban conditions in a city design context. Neutens et. al. (2011) has pointed out the need “to develop stand-alone, open-source" procedures that are completely independent but compatible with popular commercial GIS packages.

3. Space time models for time-sensitive passenger travel modes

Although the representation of the transport system within space-time models has evolved over time with increasing fidelity, there remains a lack of methods that includes passenger transport as a travel mode that is time-sensitive. Related work MASTIC in past literature as a space time model provides a conceptual basis for the comparison between different travel modes in alternative urban conditions with considerations of interpersonal differences (Dijst, de Jong and van Eck, 2002; Ritsema van Eck, Burghouwt and Dijst, 2005). However, it is limited in the representation of the transport system.

Chapter 3 - Theoretical framework

3.1 Chapter introduction

The following section describes and discuss the theoretical framework in this study for the development of a computation-enabled analytical construct. The computation-enabled analytical construct to be developed in this study consists of two parts.

The first part is the development of a computation enabled analytical framework aims to address the need to understand and contribute to the wider problem of sustainable transport system and sustainable travel activities for transport-integrated city design. As identified in the literature review, there is a lack of an appropriate analytical construct for transport-integrated city design in architecture that considers passenger transport – a travel mode that has a difficult position in its role in sustainability, an issue explained in the background section 1.6 pg62-67.

The second part is the development of a computational space time model for alternative urban condition – a research gap identified in the literature review. The potential for a space time model to explore the opportunities for the mode change with considerations of passenger transport has been demonstrated in related literature (Lenntorp, 1978; Dijst, de Jong and van Eck, 2002). However, the underlying space time model for alternative urban condition (Lenntorp, 1976; Dijst, 1995) is relatively underdeveloped compared to more recent advancement in closely related studies of existing conditions (Miller, 1991; Kwan, 2004a).

This chapter first describes the wider theoretical contexts relevant to this study and position the study within the wider theoretical contexts (3.2). The second section (3.3) further discuss the reasons and justification for the selection of a space time approach compared to the other two analytical approaches. The third section (3.4) describes the specific type of simulative space time models for alternative urban conditions that is to be further developed in this study and the relevant time geography theoretical constructs.

3.2 Wider theoretical context related to research topic

3.2.1 Determinism, possibilism and probabilism

This study consists of the notion of transport and the notion of travel, as previously distinguished in the background section 1.4.2.1 pg34 as different but overlapping notions. In the context of this study, transport activities and transport system are part of the environment; travel activities and the act to travel is performed by people.

A meta-theoretical question is the **theoretical assumptions of relationships between people and environment** which has undergone much ongoing and historical wider debate in geography as well as its variations from an architectural perspective. It is not the aim of this relatively small study to propose an answer to the wider debate but to clarify the orientation and theoretical position in this study for the development of a computational analytical framework towards sustainable travel activities and to support sustainable travel activities.

There are two commitments in spatial planning and design oriented applied research that needs to be considered, relevant to the aim of constructing a computational analytical framework for transport-integrated city design:
(1) an assumption that physical space matters; if physical space does not matter then there is no need to plan or design physical space
(2) desirable goals usually involve how people respond or use the physical space, beyond complete control of planning and design.

While the discussion revolves around physical space, the same applies for policy and service planning in the form of instruments/interventions/initiatives towards certain goals that are deemed desirable (Anderson, Kanaroglou and Miller, 1996). An aim to understand how to create/arrange/layout/configure physical space, new transport service provisions, considerations in the geographical distribution of spatial functions and considerations in facility locations (Næss, 2016) informed by either qualitative studies or quantitative measures inevitably results in an architectural (Hillier *et al.*, 1986) or a planning question (Næss, 2016) of determinism.

There are three basic perspectives that directly draws relations between environment and people-related aspects (1) geographic determinism, (2) geographic and (3) geographic probabilism in a fundamental research context relevant to planning (Næss, 2016). In the applied research context relevant to planning and design, there are three similar positions on how changes in the environment can lead to wider outcomes that are related to people (1) architectural determinism, (2) architectural possibilism and (3) architectural probabilism. Devlin (2010) articulates in an architectural context where "determinism suggests that the design creates the outcome; probabilism suggest that design makes a certain outcome more likely, and possibilism suggest that an environment creates the opportunity for an outcome".

Fundamental research that investigates the connection between the physical environment and people, and by extension, applied research to provide insight to influence planning and design spatial solutions towards desirable outcomes based on fundamental research are challenged by the problems of physical determinism (Jabareen and Zilberman, 2016).

The following excerpt from Franck (1984) discussion highlights four problems of physical determinism associated with environment-behaviour research:

1. *"Exaggerating the influence of the physical environment on behaviour by ignoring or underestimating the influence of other factors*
2. *Assuming that the physical environment has only direct effects on behaviour*
3. *Portraying people as passive participants in the environment-behaviour relation and, more specifically, as having no goals and making no choices*

4. *Always assuming that the environment is a given and immutable entity and ignoring the creation or modification of environments"*

A common understanding in urban design is that "the creation or modification of environment merely creates potentials, what happens depends on the choice made by people." (Carmona *et al.*, 2012) Extending this view, this is relevant to the research problem related to transport/travel-related sustainability in the role of physical environment and passenger transport services as they provide one of the necessary but not sufficient condition for transport/travel-related sustainability at least in the environmental dimension.

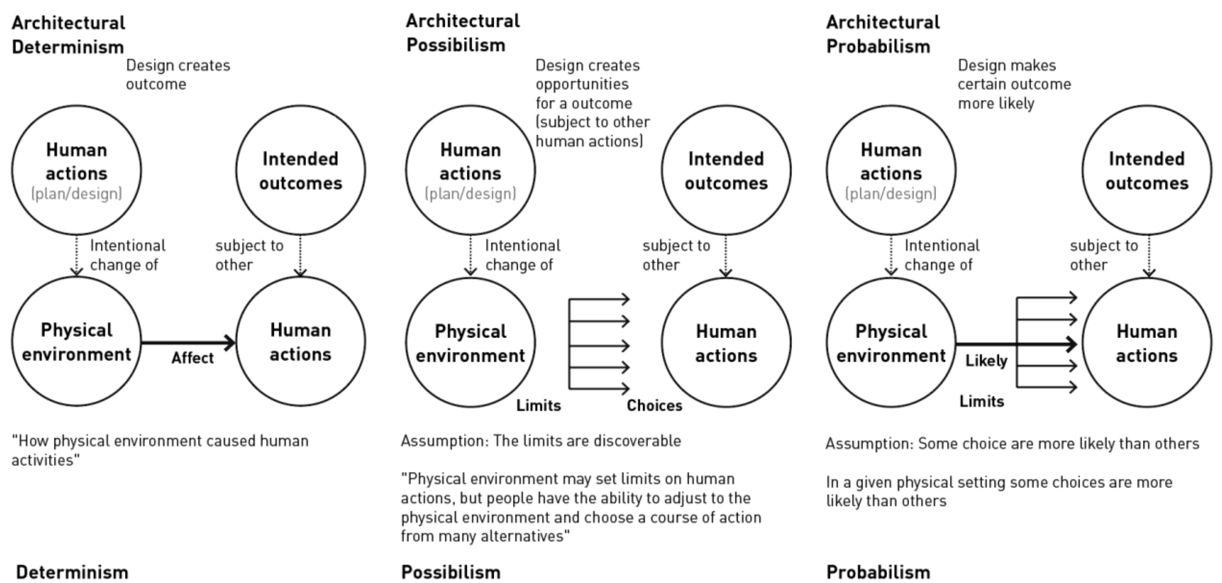

Figure 14 architectural determinism, architectural possibilism and architectural probabilism in an applied research context and determinism, possibilism and probabilism in a fundamental research context (partially adopted from Matthews (2014))

This study is closest to a possibilism position. The provision of transport services, the distribution of urban opportunities is viewed in this study as facilitating and constraining conditions for the sustainability of transport system and travel activities.

In a wider planning context, there are some conceptions have an emphasis towards questions of societal organisations and the process of planning and less about the physical spatial solutions. As Naess (2016) pointed out, there is a difference between process of planning and "the contents and consequences of the spatial solutions" related to Faludi's (1973) distinction, the former being **theory of planning** and the latter **theory in/for planning.**

There are two points of relevance to this study. (1) "Theory of planning" (e.g. rational-comprehensive, communicative) is relevant to the role of computation-enabled analytical framework and the interpretations of results towards different notions of transport/travel-related sustainability. (2) "Theory for planning" is relevant to the content of what is being analysed in the underlying space time model related to the potential travel activities in alternative urban conditions.

3.3 What can be known through a computation-enabled analytical construct?

This underlying theoretical question in this study centred on the development of a computation-enabled analytical construct for transport-integrated city design towards sustainable transport system and to support sustainable travel activities can be understood in two parts:

(1) the considerations of an ontological position of what is real and an epistemological position of what can be known through a computational analytical construct

(2) the role of computational analytical construct for transport-integrated city design towards a sustainable transport system and to support sustainable travel activities.

3.3.1 Part 1: The considerations of ontological position

What is real and epistemological position of what can be known of unrealised alternative urban conditions through a computational analytical construct?

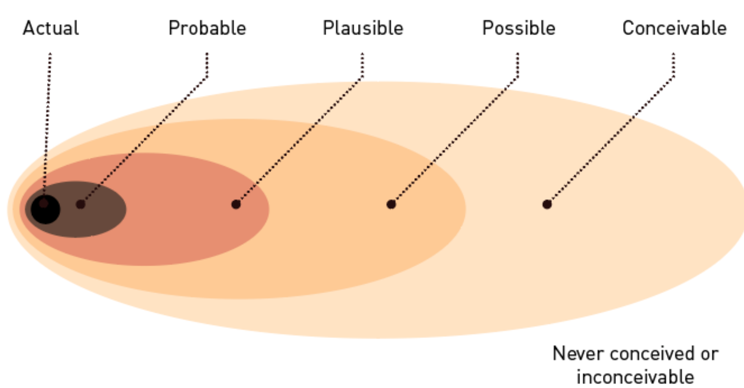

Figure 15 A range of future-oriented descriptions to actual description (Barkin and Sjober, 2017), similar depiction found in the concept of "future cone" (Hancock and Bezold, 1994)

Results from computational analytical constructs at the applied end of a fundamental-applied continuum are not the "actual" but they can range from probable, plausible, possible and conceivable depending on the theories underpinning the analytical constructs.

There are three identified research paths from fundamental research to applied research based on existing computational analytical constructs identified from the literature review:

1. **Metrics of urban characteristics**-interpretation-correlation-data corresponds to the built-environment-focus fundamental research context and the change in built environment especially in urban design in the applied context

2. **Model of urban systems**-travel behaviour-data corresponds to a combination of the people-focus and environment-focus fundamental research context and the change in both built environment and people-related aspects through a behavioural approach
3. **Space time approach**-person based accessibility-activity programme contains elements contains both built environment and people-related aspects but it has been primarily used for understanding changes from a point of view of inhabitants/citizen within the environment given the services, facilities and constraints in the environment.

Three specific lines of research corresponding to the above are identified through recent analytical constructs in this study. These are further discussed in terms of their underlying theoretical framework, assumptions and their relevance to the main research topic in this study in search for an appropriate computational analytical construct to facilitate scenario modelling and diagnostic assessment of alternative urban conditions relating the potential for travel-based activities and sustainable urban transport systems.

The three specific lines of research are:

1. **Space syntax** with its own unique formulation of metrics describing urban characteristics directly related to movement of people with substantial difference to correlational studies using metrics such as density and diversity
2. **Transport/travel demand modelling** within a wider conceptual understanding of "land use and transport feedback cycle" (M Wegener, 2004) for integrated model of urban systems
3. **Space time models**, in particular the early work when the specific analytical framework and underlying space time model was developed from Hagerstrand's space-time geography within an applied context of urban planning and transport improvements (Lenntorp, 1999).

While there are other computational analytical constructs that are used to study movements of people ranging from micro-scale pedestrian simulation to macro-scale migration patterns, the three selected lines of research are selected around potential travel activities in wider urban regions. In addition, there are also computational analytical constructs that aims at a description of movement of people, for example in the form of visualisation or representation of current or past movement patterns, they are excluded as they do not directly provide insight on future alternative urban conditions.

It is important to note that each identified lines of research consist of multiple and evolving analytical constructs, which is not discussed here in detail but to point out the theoretical orientations and its implications in applied research for transport-integrated city design relevant to this study.

While the three lines of research involve potential travel activities, they operate in different ways from fundamental research to applied research. However, there are notable overlaps and combinations. For example, since space syntax measure correlates with vehicular traffic it's axial map has been used as a validation method in a study with use of a transport demand model (SATURN) (see section 2.2.3 pg76) for an emission estimation model (Brandon, Lombardi and Bentivegna, 2003). Another overlap found in literature is the conceptualisations from space-time approaches and activity-based approach for travel demand models.

	Metrics of urban characteristics-interpretation-correlation-data	**Model of urban systems-travel behaviour-data**	**Space-time approach-person based accessibility-activity programme**
Theoretical	Space syntax theory (Hillier and Hanson, 1984); Space is the machine: A configurational theory of architecture (Hillier, 1996)	Location theory and urban economics traditions (see historical overview (Batty, 2008a))	Time geography (Hagerstrand, 1970)
Related conceptual framework (wider conceptual framework for understanding how cities work)	Cities as movement economies (Hillier, 1996)	"Land-use transport feedback cycle" (M Wegener, 2004)	Travel behaviour conceptual framework considering space-time and activity (van Acker, van Wee and Witlox, 2010)
Methodological	Space syntax analytical techniques (e.g. integration, choice, depth)	Model of urban systems (Land use transport integrated model LUTI: Travel demand model TDM and Land use model LUM); With specific attention to TDM	Space-time model (as descriptive notation in classical time geography, H.Miller's analytical time geography and Lenntorp/Dijst simulation
Towards applied research – change in urban environment	Focus on change in environment with an interpretation of likely outcomes based on research findings from fundamental research supported by theories of relationships between metrics and outcome. E.g. Theory of natural movement (Hillier)	Focuses on the estimation of travel demand to quantified amount of transport activities, used in a wider land use and transport integrated model	The implications of changes in environment to opportunities for activities to be conducted (Jones, 1983)
Urban environment-related aspects (fundamental research)	Represent and quantify urban environment as independent variables in statistical analysis observable behaviour patterns as dependent variables, typically theory testing on movement patterns.	Fundamental research typically focuses on land use change (e.g. CA transition rules) and location choice (e.g. residential location choice)	Use of analytical construct in research to understand mode change opportunities (Dijst, 1995), joint accessibility (Schwanen & Neuten), domain-specific survey (Jones, Kwan),
People-related aspects		Fundamental research: Behavioural	

(fundamental research)		approaches typically under a rational choice assumption and discrete choice analysis (McFadden, Ben-Akiva)	empirical studies (Kwan)
Towards applied research – change in people-related aspects	N/A	Applied research embedded within TDM and LUM as choice models. Transport policy analysis e.g. ridesharing, road pricing. Activity-based approach concepts developed from space-time approaches.	Concepts adopted in activity-based modelling approach as part of travel demand model
Examples of analytical constructs	Spatial integration axial integration angular integration (within space syntax version of accessibility based on topological centrality – fewest turns)	MARS (Pfaffenbichler, 2003) with a spatial interaction-based formulation for the transport sub-model Operational model corresponding to the “land use transport feedback cycle” (Wegener, 1996) Both includes a four-step model for the transport system	PESASP (Lenntorp, 1976, 1978) MASTIC (Dijst, 1995, 1999; Dijst and Vidakovic, 2000)
Applied constructs as analysis of changes	Analytical techniques – from spatial configuration/layout to likely outcomes	Modelling land use and transport policies case study in Madrid with MARS (Alonso and Wang, 2017)	Case study in Karlstad with PESASP (Lenntorp, 1978) Case study in Zoetemeer with MASTIC (Dijst, de Jong and van Eck, 2002)
Theoretical reasoning for applied constructs as analysis of changes	“distortion in space created by the presence of objects” create the pattern of co-presence (Hillier *et al.*, 2010) “the system of natural co-presence and co-awareness created by spatial design and realised through movement” (Hillier, 1996)	Scenario analysis (Waddell and Ulfarsson, 2004);	Human Activity approach (Jones, 1983)
Key analytical concepts related to movement of people	“Line of sight” for axial line (Bafna, 2003) Number of turns	Transport/travel models: (Macro variations) Spatial interaction; Modal split	Activity programme – locations of activity participation and travel required to connect

	"Turn as little as possible" for angular measures (Turner, 2000) Minimum path using on different distance metrics – metric, topological and angular	(Micro variations) Trips/Tour/Activity pattern; Mode choice	them, usually within a day (Dijst, Lenntorp) Space-time anchor (Neutens, Witlox and Demaeyer, 2007)
Key concepts	Spatial configuration - Topology of spaces (a mathematical description of how defined spatial units are connected to each other)	Model of urban system: Urban change and transformation as a process - Simulation of urban systems; Global structure develops from local processes	Time and space as resources; Capability, authority and coupling constraints – adopted in urban-related studies in the form of time-activities (Chapin, 1971) and person-based accessibility (Miller, 2007)
Related concepts	Spatial cognition – Axial line (Penn, 2003)	Simulation of social phenomenon in an urban context (Wu, 2002); Hagerstrand spatial diffusion (Hagerstrand, 1965); Multi-agent systems for urban planning (Crooks, Patel and Wise, 2014); Complexity theories of cities (Portugali, 2011)	Activity/Action space Person-based accessibility Social sequence/life path trajectory
Related fields of study	Urban morphology (space syntax as an urban morphological approach (Oliveira, 2016)) Wayfinding and cognitive maps	Planning support systems (Geertman and Stillwell, 2004); Transport planning; Economics; Geography; Urban studies (with a complexity orientation)	Human geography (Ellegård; Schwanen) Activity-based travel analysis (Arentze) Geographic Information Science/ Geocomputation (H Miller; Kwan)
Identified meta-theoretical orientation in fundamental research	Expressed traits of positivism - theory and model develop for their predictive value of patterns related to human actions specific to "place structure". Acknowledges other methods for subjective dimensions of place; include cognitive aspects in the formulation of representation and distance measure	Expressed traits of positivism - theory and model usually develop for their predictive value; representation of behaviour the related developments in social simulation, however, is usually a non-empirical type of research to locate plausible scientific explanation to a macro phenomenon from micro interactions	"Evaluating potential behaviour rather than analysing actual behaviour and is essentially concerned with patterns of time-space allocation rather than time-space use" (Pickup and Town, 1981)

Identified meta-theoretical orientation in applied research	Probabilistic - Spatial configuration likely to produce certain patterns of co-presence and movements	Probability distributions in choice models due to lack of information for a precise statement; Multiple possible outcomes in policy analysis e.g. MARS for Possible development paths at the macro scale (Jaensirisak et al., 2015))	Possibilities within constraints e.g. PESASP – analysis of possible combinations of activities in time and space
Key authors	Hillier and Hanson; Penn; Peponis	E Miller; T Azentze; H Timmermans; Batty;	Hagerstrand; Lenntorp; Dijst

Table 12: Summary of environment/people orientations of three fundamental-applied research paths

Each of these lines of research have a long history of development and had evolved over time. The aim of this section is to understand the fundamental-applied connections, and the find out how each line of research produce insight of an unrealised condition.

Space syntax

Space syntax provides a set of unique ways significantly different from other spatial metrics to describe space, in particular, "space" that is commonly conceived and drawn in an urban architectural context, and the relationships between space within buildings and urban environments in mathematical terms - in the form of topology based on graph theory from discrete mathematics. There are multiple analytical constructs that have been formulated as metrics under space syntax and have been evolving since (Oliveira, 2016). The general elements include (1) representation – e.g. axial line, segment, which is then constructed as a dual network graph (2) distance measure – e.g. metric, topological, angular (3) measure on the graph includes connectivity, integration, choice.

At an urban scale, spatial configuration as a concept within space syntax in its analytical form is represented as a pattern of lines described as "spatial integration". "Spatial integration" consist of an integration value associated to each line, the value of each line reflects its' topological depth "from all other lines in the system" (Hillier, 1996).

Space syntax analysis in an urban scale focuses on "space and the relationships between space and movement", in particular, pedestrian and vehicular movement (Oliveira, 2016). Hiller et al (1993) theory of natural movement suggests the layout configuration is the primary generator of movement patterns with some exceptions (Hillier and Iida, 2005). Movement pattern correlations to space syntax measures (spatial integration) was initially based on patterns of pedestrian movements – average flow of people at certain point of observation, later studies found vehicular patterns correlates with space syntax measures (Penn *et al.*, 1998). There are multiple space syntax methods in terms of its distance measure such as metric, topological and angular (Turner, 2000) and representations including axial lines and axial segment. They correlates with movement the comparison between them in the same situation has been studied (Hillier and Iida, 2005). In addition to the study of pedestrian and vehicular movements, “theory of natural movement economic process” (Hillier *et al.*, 1993) includes the association between spatial configuration of street and the distribution of economic activities (van Nes, 2014).

In an applied context, space syntax metrics are used as a predictive metrics for pedestrian and vehicular pattern. For example, the higher the integration value a higher pedestrian density is expected (Hillier, 1996), based on an interpretation of the theory of natural movement. “spatial integration”, “spatial connectivity” (Öztürk *et al.*, 2018) and “angular segment analysis” (Charalambous and Mavridou, 2012) and “spatial connectivity” has been framed as measures of spatial accessibility. Although space syntax-based accessibility falls under a general class of topological measures, it differs from other types of accessibility measures (see section 2.2.4 literature review on accessibility pg83-88) in that accessibility is defined as “most accessible locations are not necessarily those closest to all other locations in terms of metric distances, but rather those closest in terms of topological turns” (Charalambous and Mavridou, 2012) which has a basis found in cognitive behaviour of pedestrian path choice.

Transport/travel demand model

It is well known in transport modelling literature that forecasting and estimating quantifiable travel demand in an area towards a quantified estimated value of traffic volume within transport infrastructure is one of the main purpose of transport model since the development of the four step model as early as the 1960s (McNally, 2000b). In brief, the first three steps provide estimates on travel demand and the fourth step of “traffic assignment” provide estimate of the distribution of transport activities given the transport infrastructure.

Simulation model-based analysis are commonly developed and used within a transport planning context. Transport/travel Demand Models (TDM) are known to be applied in transport planning practice in the UK (UK Department for Transport, 2013). For example, Dynamic Integrated Assignment and Demand modelling (DIADEM) by Atkins and DfT that make use of Simulation and Assignment of Traffic to Urban Road Network (SATURAN) developed in ITS, Leeds in the 1970s. Not all TDMs are the same, new TDMs and their formulation as a simulation system are actively being developed in academia as well as by companies providing consulting services for transport related analysis and development of commercial software packages. For example, PTV VISSIM and Senozon supported by research in the underlying formulation of specific types of models such as car-following model by Wiedemann (1974) in the former and Matsim for the later as a microsimulation developed in a research context (Balmer, 2007). Examples of methodological development in academic literature include ALBATROSS (A Learning Based Transportation Oriented Simulation System) (Arentze and Timmermans, 2000), TASHA (Travel and Activity Scheduler for Household Agents) (Miller and Roorda, 2003), CEMDAP (Comprehensive Econometric Microsimulator for Daily Activity-travel Patterns) (Pinjari *et al.*, 2008).

Transport Integrated (LUTI) models is actively being developed in an academic research context, which includes the combined interaction of TDM (Travel Demand Models) and LUM (Land Use Models). For example, ALBATROSS has been developed to interface with FEATHERS (Forecasting Evolutionary Activity-Travel of Household and their Environmental Repercussion) (Janssens *et al.*, 2008) and TASHA interfaces with ILUTE (Land Use Transport Integrated simulation system) (Salvini and Miller, 2005)

The recent trend of development in approaches to travel demand model is known to be shifting towards individual-based or at a finer grain unit in contrast to a conventional four step model with spatial interaction where the macro movement are conceptualised and operationalised as flows between zones. From an aggregated approach of trip-based four step models towards a more disaggregated “behavioural-oriented approach” with the inclusion of an element of travel behaviour is a response to evaluation needs from “long term investment” such as new road building to “shorter term congestion management policies” such as road pricing (Bhat and Koppelman, 2003)**.** The focus of transport/travel demand has shifted from transport demand towards travel demand with the wider context of arguments against “predict and provide” mainly referring to road building and greater emphasis on transport policies to manage travel demand.

Within a research context, a common research aim is to produce a model from a set of assumptions calibrated to the target situation and validated for its ability to reproduce the past and historical situation of an urban area to a defined degree of accuracy through simulation. They typically follow a general process of model development, verification, calibration and validation towards a predictive outcome by back testing to a degree of accuracy.

There are two main areas of development in transport/travel demand models towards the applied purpose of design, policy and urban planning (1) models to predict (2) sketch planning models.

Models to “predict”

The typical aim of TDM is to **forecast future demands** towards **changes to the transport infrastructure**, to assess the transport demand due to **changes in urban developments** or to assess the travel demand due **to changes in transport policy**. In the most applied end, the distribution of transport activities across space and transport infrastructure. TDM is typically data intensive and require large amount of time and effort to develop both in the system development phase (construct, model and method) as well as the instantiation phases when applied to a specific urban context with associated activities in data collection, data input, calibration and validation.

This purpose persists and is evident in current transport planning practices with a focus on the distribution of transport activities across space and transport infrastructure, for example, UK Transport Analysis Guidance (UK Department for Transport, 2013) and the use of packages such as SATURN (van Vliet, 1982; Van Vliet, 2009) for “traffic assignment” a procedure to associate trips to routes in a model for a distribution of traffic across the road network), Paramics (Smith, Duncan and Druitt, 1995) for pedestrian movements and EMME/2 (Babin *et al.*, 1982) for public transport assignment to estimate the number of passenger on segments within a public transport network.

Sketch planning models
The second area of development can be identified as related to a **sketch planning approach**. "Sketch planning" may have different meaning in different context depending on specific purposes. "Sketch planning tools" can be found in transport-related planning studies to provide an estimate of **travel demand** in an urban area. It is said to be a complimentary alternative to predictive models and provides a coarse estimate of travel demand at a reduce development cost, time and effort that can be more sensitive to specific policies and local conditions (Difiglio and Reed, 1975) and "provide quick response and limited data-collection requirements" (Ortúzar and Willumsen, 2011, p. 430).

In a wider sense, "sketch planning" can also be found in urban planning in the context of developing planning support systems for urban development (Hopkins, 1999). According to Harris (Harris, 2001), sketch planning consists of three general parts (1) "specify a set of interventions, a plan or part of a plan" (2) "determine the probable consequences or outcomes of this intervention" and (3) "evaluate these outcomes with reference to the goals being pursued".

A common characteristic in sketch planning approaches is their aim to **explore** which differs from TDM with an aim to **predict**. In transport modelling, construct/theory and model/method activities are similar to a TDM approach. There are substantial differences when analytical model is to be applied in a context. Generalised forms of data and assumptions are typically employed using **parameters and relationships deemed to be transferable** from previous studies and/or from a different context. (Martin and Mcguckin, 1998) Although it is a faster way to explore possible outcomes, the result is not comparable to a predictive model. In addition, calibration, verification and validation are not possible due to generalised data inputs, meaning that they cannot be predictive. Sketch planning approach generally **facilitates the analysis of scenarios** which involves setting up a baseline scenario with interventions and changes tested against the baseline to understand the implications of changes.

In the wider context of land use transport integrated models. A widely cited conceptualisation of the interaction between land use and transport system is the "land use transport feedback cycle" (M Wegener, 2004). The "land use transport feedback cycle" identifies the connection between land use and transport system as "accessibility" and "activities".

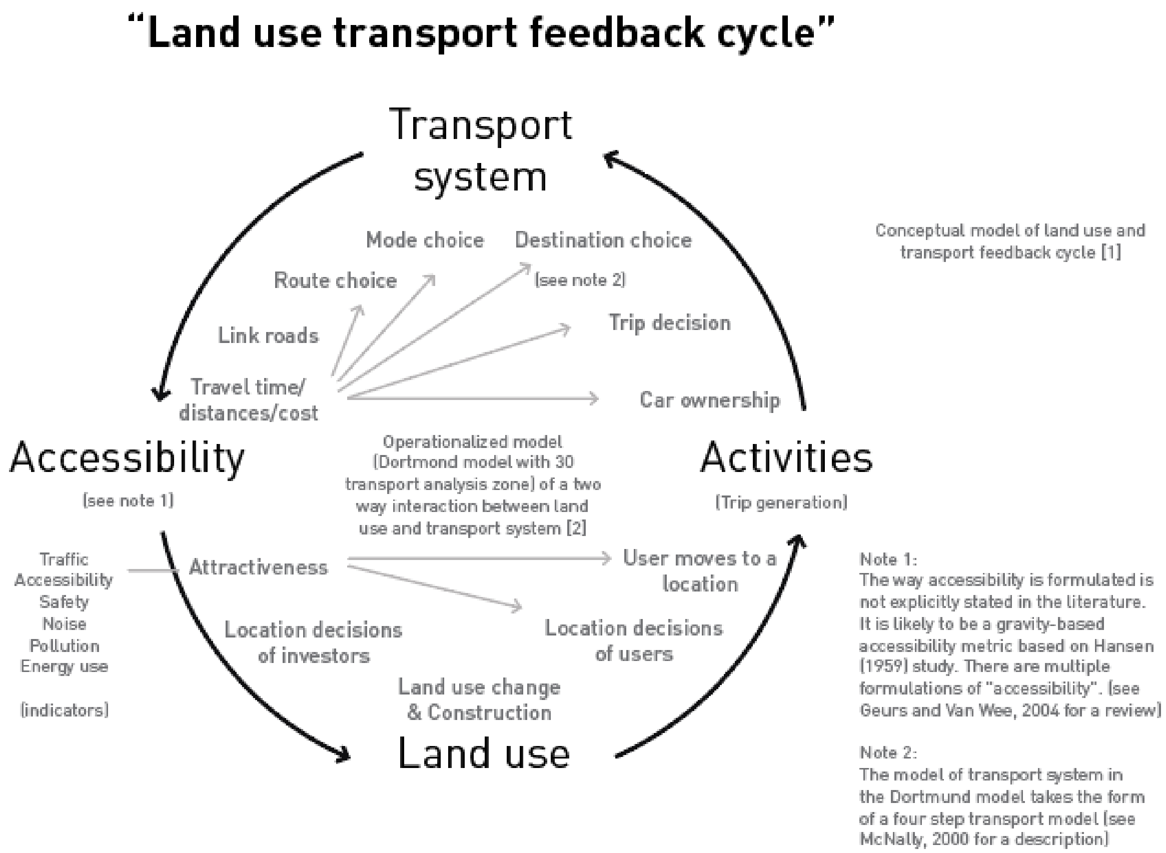

Figure 16 "land-use transport feedback cycle" (Michael Wegener, 2004) with example of operational model for each step (Wegener, 1996)

Under this conceptual framework connecting land use and transport as a model of urban system, land use is related to transport system through travel activities – the need to travel to overcome the spacing of different land functions distributed in physical space; transport system in turn relates to land use through the notion of accessibility – the decision to live/work or develop in a certain location is influenced by the accessibility of the location – supported by earlier studies in how accessibility shapes land use (Hansen, 1959).

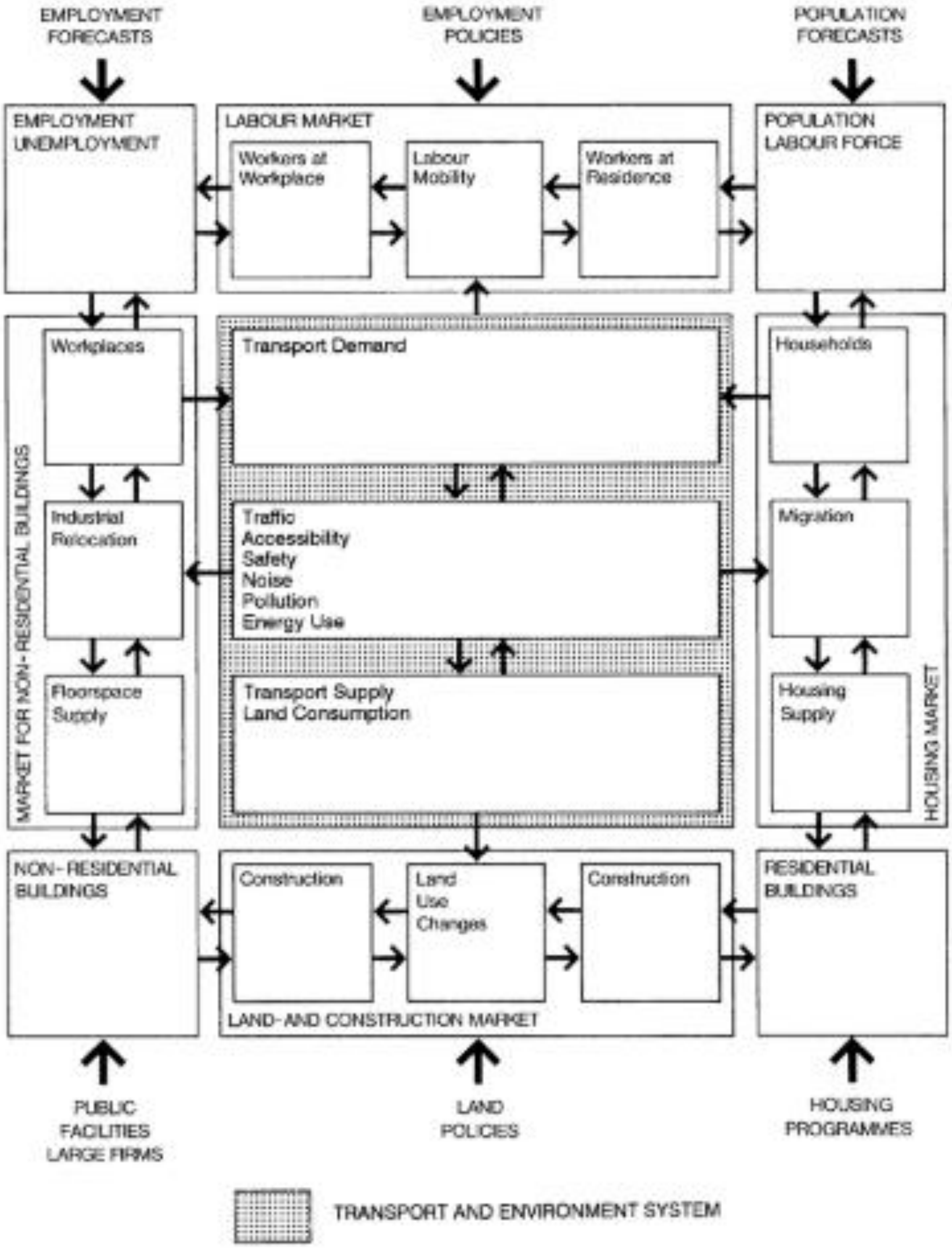

Figure 17 Major sub-systems of Wegner's Dortmund model (Wegener, 1996)

The operationalised model by Wegner (Wegener, 1996) to investigate the reduction of CO_2 emissions by reorganising urban activities illustrates how the conceptual framework can be operationalised as a land use transport integrated model. In the urban model, the transport system is modelled under a four-step model framework for transport demand, and the land use model is modelled as a supply-side land and construction market model.

As earlier mentioned, there has been a movement towards more disaggregated (Iacono, Levinson and El-Geneidy, 2008), sometimes described as finer grain (Gerber *et al.*, 2018), higher resolution (Wegener, 2000), high fidelity (Miller, 2014) model of both space and human activities in the evolution of LUTI. The same has been the case for travel demand models with more focus on the individual travel behaviour within models driven by policy relevant analysis (Bhat and Koppelman, 2003)

Within transport/travel models there is a concept of **mode choice** relevant to all identified notions of travel/transport related sustainability where multiple transport/travel modes are considered. A typical mode choice model is formulated as discrete choice model with associated discrete choice analysis from transport economics (see section 2.2.2.3 literature review for a description pg74). In brief, a mode choice model provides the probability of an individual choosing an option amongst a “choice set” – the alternative modes between an origin and a destination. “Probability” under this conception is used not as a way to describe the probability amongst all possible ways in which choice can be made but as a way to describe choice with the lack of information for a precise statement.

Although the economic perspective it prominent in transport/travel models to describe and model travel behaviour. How travel behaviour can be understood and how it is operationalised in applied fields is still and open question and undergoing active development especially around activity-based approaches (see section 2.3 state-of-the-art review pg89). Given that there are advances in both the modelling approaches and other behavioural theories, there had been attempts to construct an alternative comprehensive conceptual framework that offers a different view of the transport aspects in terms of travel as well as a more disaggregate view of space in terms of locational properties compared to the conceptual framework of “land use transport feedback cycle”. van Acker et. al. (2010) conceptual framework is a combination of theories from time geography, activity-based approach and social psychology.

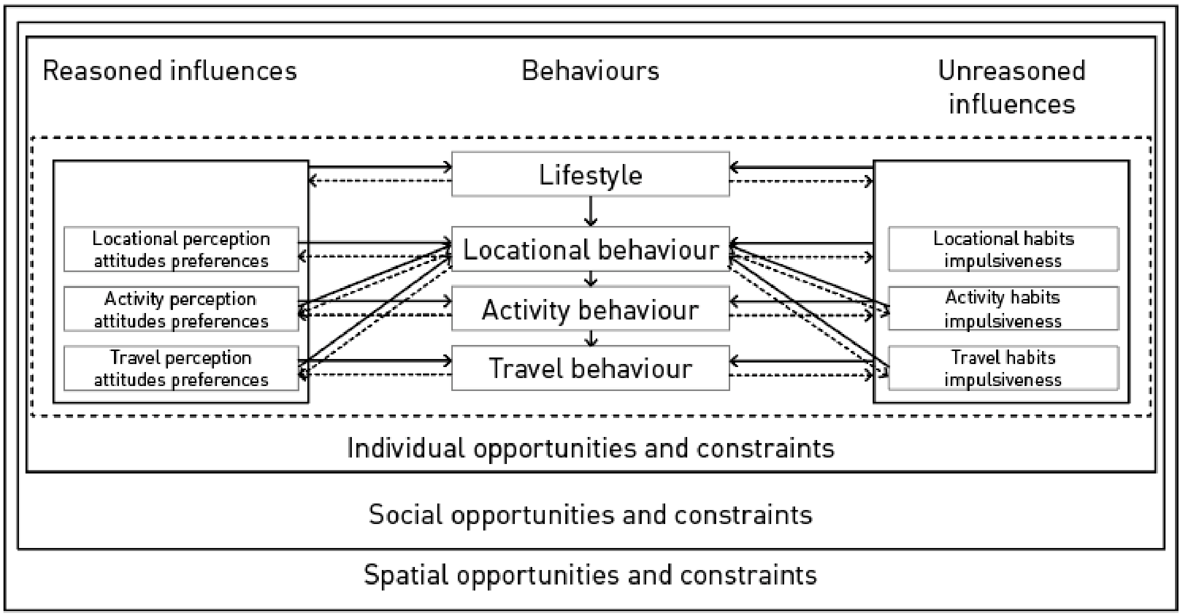

Figure 18 conceptual framework of travel behaviour (van Acker, van Wee and Witlox, 2010)

Space-time model

What is space-time model?
"Space-time model**"** in this study refers to models based on space-time or time geography framework. The specific line of thought can be found in the early space-time models that informed the activity-based approach to travel analysis for transport modelling (Rasouli and Timmermans, 2014) and form the basis for the computation of person-based accessibility measures (Kwan and Hong, 1998). The original root of space-time model can be traced back to Lenntorp's analytical framework operationalised as Program Evaluating the Set of Alternative Sample Paths (PESASP) (Lenntorp, 1976). PEASASP was described by Lenntorp as:

"The PESASP simulation model maps the set of alternative ways in which a particular activity programme can possibly be carried out. The number and kinds of these activities are a function of the combined qualities of the individual and the environment. The individual has to make choices which fall within the set of possible alternatives, although the model does not pre-determine which choices will be made. A person's behaviour is controlled both by structure of the existing environment and by individual preference of which the latter are less known." (Lenntorp, 1978)

PESASP is an operational model with a combination of a systematic description of urban environment, the transport system and daily activity programmes. The geographical information side is rudimentary by modern standard, yet revolutionary at the time as a "digital multi-modal transportation network that included public transport, bicycle and walking as alternative travel mode" considering there is a "lack of digital geographical data and computer resources" at the time (Kwan, 2004a).

The work that followed by Dijst MASTIC (Dijst, 1995) has a similar underlying structure with the addition of the concept of “action space” (Dijst, 1999) for urban planning.

The corresponding applied research type studies can be found in Lenntorp (Lenntorp, 1978) use of PESASP to study public travel possibilities in the city of Karlstad given urban environment from a citizen/user perspective and Dijst et.al. (2002) use of MASTIC to study opportunities for mode changes given urban environment and travel diaries of residents in Zoetermeer.

A different line of research brought space-time model into fundamental research with empirical studies of sociodemographic phenomenon in geography. This line of research is mainly developed by Kwan that evolved from early work connecting cognitive theories with space time model and geocomputation. The first known model is GISICAS (Golledge, Kwan and Garling, 1994) and introduced the concept of “feasible opportunity set” that includes the effect of bounded rationality in the choice set (Kwan and Golledge, 1997).

There are three types of space-time analytical constructs as **conceptual notations, analytical representation and simulative model**.

1. **Space-time conceptual notations** are descriptive visual notation of movements through space-time concepts, including space-time paths, space-time prism, potential path area (PPA), daily potential path area (DPPA).
2. **Space-time analytical representation** forms of conceptual notations (Miller and Bridwell, 2009) coupled with measurement theory produces quantitative measurements.
3. **Space-time simulative model** simulates space-time paths and the emphasis is to draw logical implications of the possible individual movement in space and time constrained by spatial and temporal urban conditions (Lenntorp, 1978). Space-time models has been adopted as the procedure for the computation of person-based accessibility based on space-time concepts.

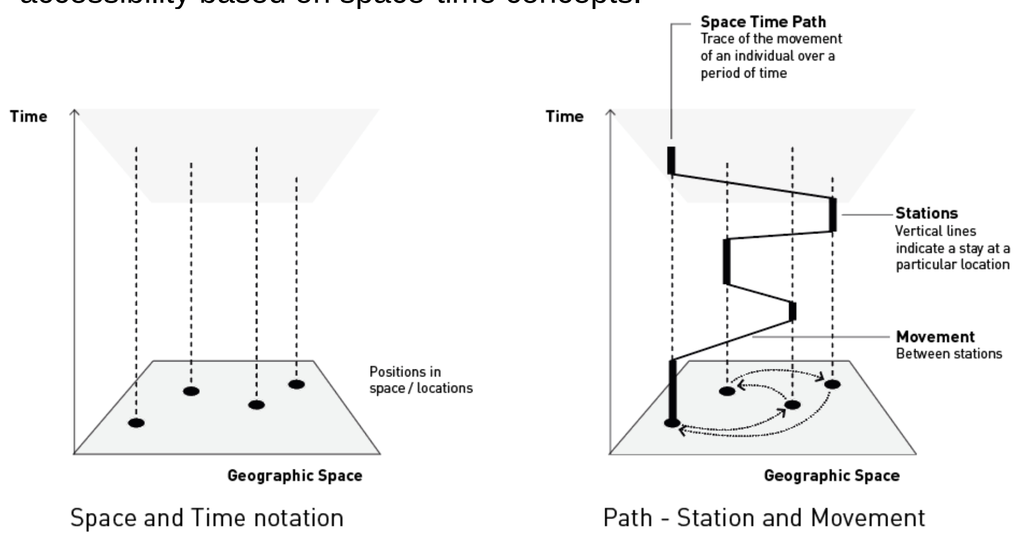

Figure 19 Space time notations from classical time geography (author’s own illustration)

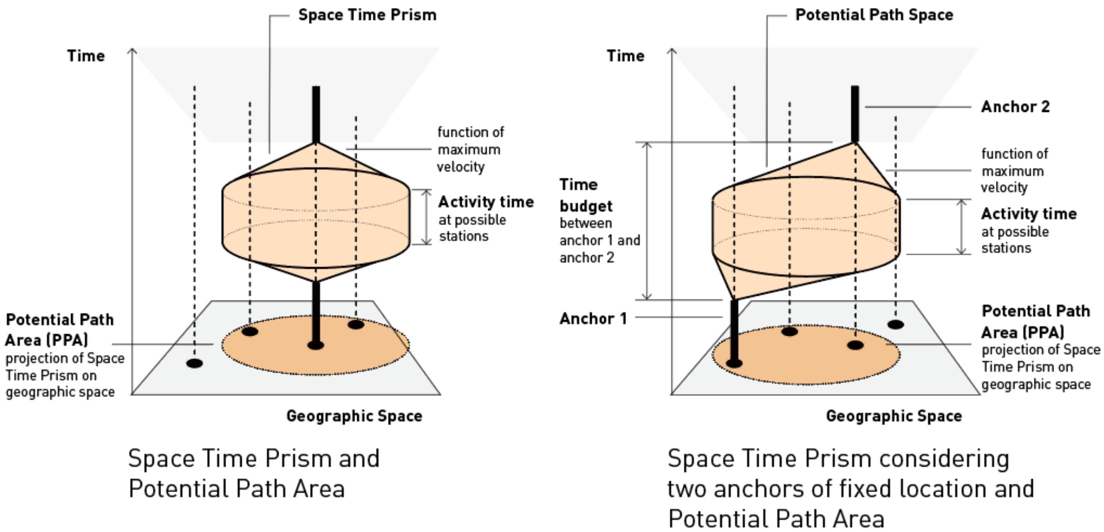

Figure 20 Space Time Prism and Potential Path Area from classical time geography (author's own illustration)

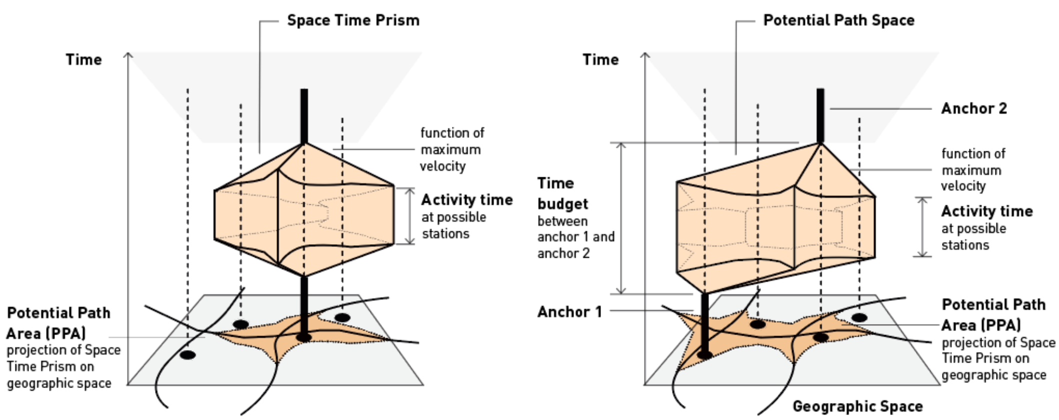

Figure 21 Network Time Prism in analytical time geography (Miller and Birdwell, 2009) (author's own illustration)

The core idea of space time models is to find the possible combinations under a certain urban space and time-sensitive condition given its facilitating and constraining property for a daily activity programme to be performed subject to an individual's space and time constraints. Daily activity programmes are a structured description of past or intended activity to be performed within a time period usually within a day of 24 hours as a sequence or in other words, "activity chains" (Lenntorp, 1978), activity pattern or activity schedules.

Understanding the possibilities for an activity programme to be performed or not within an urban condition is important because it is related to what van Acker et. al. (van Acker, van Wee and Witlox, 2010) identified as individual, social and spatial opportunities and constraints of where to live, work, conduct activities that an associated to specific opportunities of activity participation. In doing so, the possible travel activities between these opportunities of activity participation can be examined.

The concept of activity programme relates to a branch of research in the study of activity sequences both in transport-oriented studies in terms of activity pattern generation and in social-oriented studies in "human activity analysis" (Shoval and Isaacson, 2007) for the study of activity sequences. Studies in person-based accessibility that make use of the core idea relating activity programmes to urban environment, "activity programme" used in the process are empirically informed by "activity schedules" or "activity sequences" using empirical data collected from reality such as detailed travel diaries and time use diaries.

Space-time accessibility as a form of person-based accessibility (Miller, 2007) includes multiple formulations targeting different kinds of analysis. Person-based accessibility are extensions of analytical space-time constructs of PPA (Kwan and Hong, 1998). A number of advance has been made in the past with the combination of person-based accessibility and utility (Miller, 1999) and the considerations of space-time opportunities for multiple agents in terms of joint accessibility with the concept of Potential Interaction Area (Neutens *et al.*, 2007). However, there are more within the analytical constructs of PESASP and MASTIC that differentiate them from a construct that produces accessibility metrics given the required parameters.

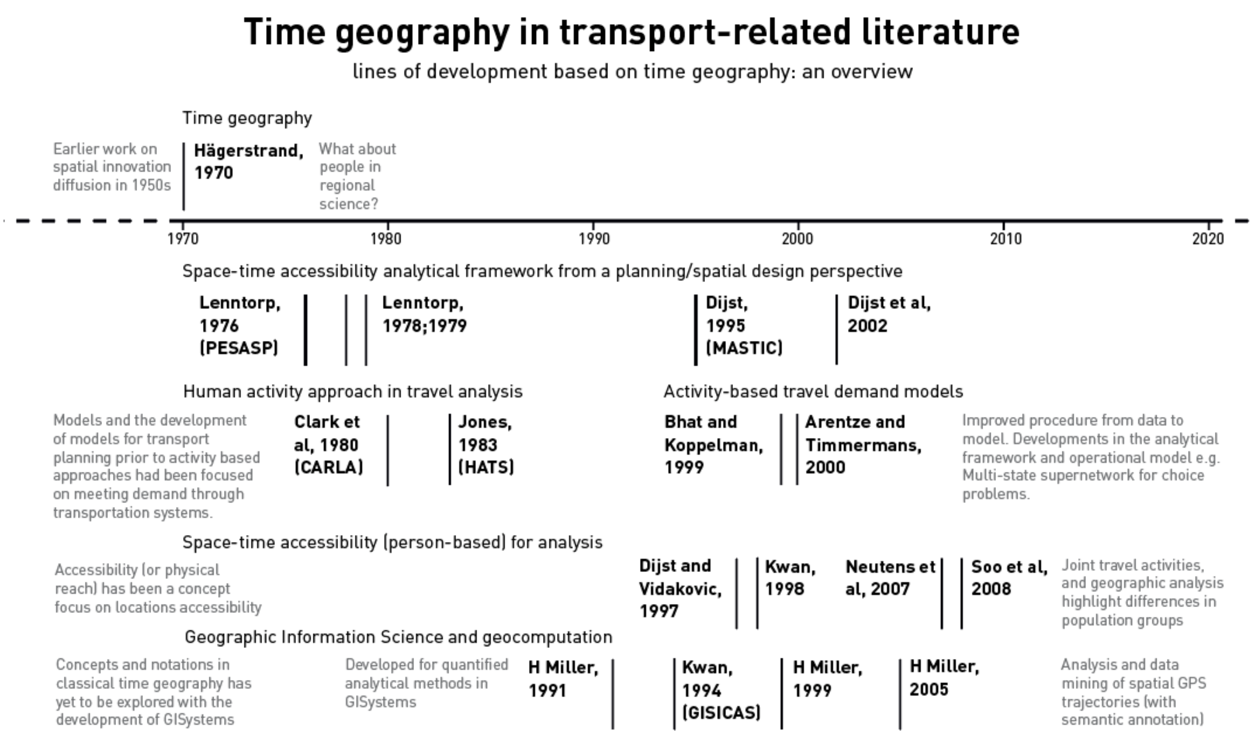

Figure 22 A timeline of key articles: time geography in transport-related literature (authors' own)

Comparisons

Space syntax in contrast to the other conceptualisation of movement from early the model of urban systems line of thought, movements are conceptualised as "spatial interactions" with flows between zones of attraction or production (see section 2.2.3.1 on four step models pg77). Penn (Penn, 2003) a space syntax axial line approach in contrast to the underlying behavioural approaches found under the model of urban systems of individual motivation and goal-directed behaviour. The use of topological and angular distance function differentiates space syntax from other approaches that relies on a geo-spatial representation of movement.

A space syntax approach considers relationship between all entities to all entities within the whole area instead of the considerations of the assumed generative parameters of individual trips usually found under model of urban systems or the possibilities of activity programmes under the space-time model line of research.

Unit of analysis	**Space syntax**	**Transport/travel demand**	**Space-time model**
Space	Urban scale: Figure ground Street network Street centre line (Liu and Jiang, 2012) Spatial configuration – map representation as axial line, segment etc	Macro variation: Transport/traffic analysis zones (TAZ) Micro variations: Transport network for routing, public transport time schedules e.g. Matsim	Opportunities for activity participation; Multimodal transport network
People	Pattern of movement (pedestrian / vehicular) and use of space (e.g. economic activities)	Marco variation: spatial interaction – flow between zones of production and attraction Meso level: activity pattern (activity-based approaches) Micro level: individual travel behaviour, in particular, mode choice probability (economic or cognitive) Possibilities of mode choice considered as choice set (a set of alternative options) within a utility function.	Individual/joint (multiple individuals) activity programme Possibilities of mode choice considered as opportunities.
Movement of people	Amount of pedestrian and vehicular movements as pattern Public transport as stops/stations	Marco variation: spatial interaction – flow between zones; multiple modes (e.g. MARS) Micro variations: mainly focused transport activities on road network (e.g. Matsim, SUMO)	Walk, drive and public transport from possible routes. Space and time sensitive.

Table 13. summary of unit of analysis between three lines of research

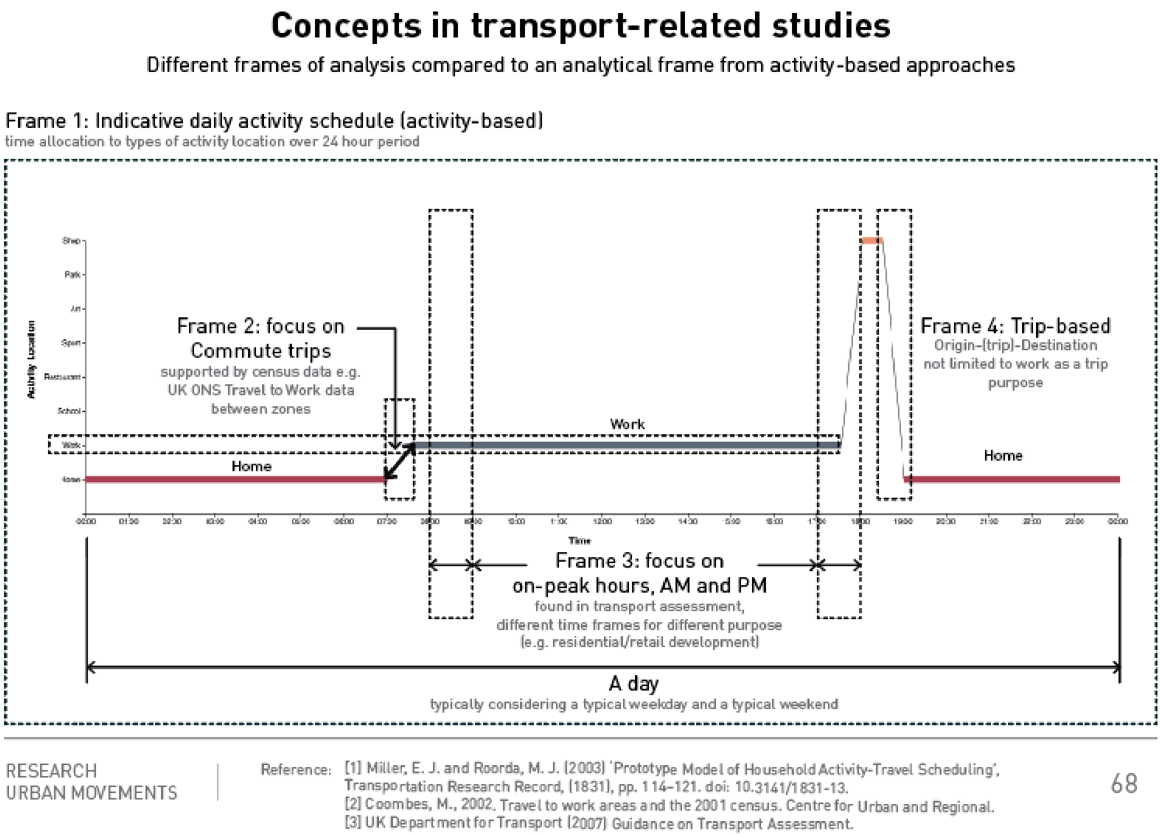

Figure 23 comparison between space-time model (frame 1 daily sequence of activity) and different unit of analysis found in transport/travel related studies (frame 2,3,4)

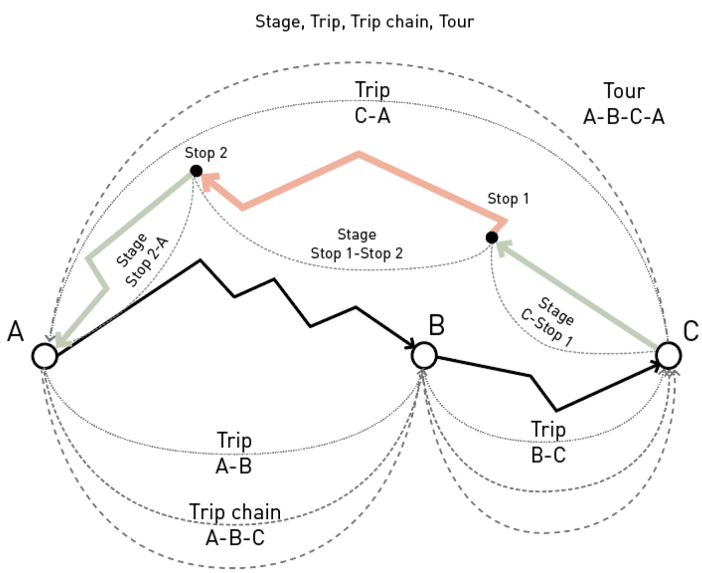

Figure 24 Trip, trip chain, tour as units of analysis

Micro-variations of travel demand models and space-time models are similar in that they both considers individuals. This is reflected in the way in which newer types of activity-based travel analysis towards travel demand models are informed by space-time models.

An activity-based approach typically considers the full activity chain over a day (frame 1), including in-home and out of home time with travel activities in between. A traditional approach to transport models however, takes the unit of analysis as one of three frames: commute trips (frame 2), on-peak hours in the morning and in the evening (frame 3), and trip-based (frame 4). While a traditional approach is framed in a way to estimate the maximum load on a transport system, a full activity chain approach enables a more comprehensive view of travel activities.

Discussion

All three lines of fundamental-applied research are said to useful in understanding potential travel activities and provide insights for policy/planning/design in an applied context, however they differ in that each has strengths and limitations in understanding certain facets of potential travel activities.

Space syntax metrics of spatial integration based on axial line that is said to correlate well with observed pedestrian and vehicular movement in different urban contexts. There is a need to consider how it operates with passenger transport as part of movement of people in urban areas. There are attempts to include passenger transport in terms of conventional public transport through the correlation between entry and exit pedestrian count and space syntax metrics (Chiaradia, Moreau and Raford, 2005) and attempts to include other forms of transport. However, space syntax is currently limited in understanding movement of people in passenger transport modes. In addition, given that the underlying principle of axial line that is based on line of sight (Bafna, 2003), it is difficult to conceive how it can relate to movement of people on passenger transport modes without an additional geo-spatial oriented analytical framework. Combining space syntax with another analytical framework has been attempted but often used space syntax analysis in its applied form. For example, the use of discrete event simulation for electric vehicles with space syntax as a predictive model to supply numerical values in the simulation (Elbanhawy, Dalton and Nassar, 2013). Another example is the use of a transport demand model (SATURN) (see section 2.2.3 for a background description pg76) validate by comparison with axial map in space syntax for an emission estimation model (Brandon, Lombardi and Bentivegna, 2003).

Space-time models demonstrates a different approach to the other two lines of research in the sense that the analytical constructs are not aimed at prediction of an outcome. They were aim at “evaluating potential behaviour rather than analysing actual behaviour and is essentially concerned with patterns of time-space allocation rather than time-space use” (Pickup and Town, 1981).

Research motivation	Space syntax	Transport/travel demand	Space-time model
1. to provide an understanding of the implications of changes on movements of people in alternative urban scenarios	In the most applied setting provide an understanding of “place structure”, in parallel to other methods and approaches (e.g. phenomenology) to understand “place character“ (van Nes, 2014) Pedestrian accessibility measures: ‘connectivity’, and ‘integration’ (Öztürk *et al.*, 2018)	Models to ‘predict’ in the most applied sense to assist planning/policy practice. Two different purpose for quantified estimated amount of transport activities (1) their distribution across the transport infrastructure (2) as policy analysis for travel demand management	Most applied variations found in the application of space-time based model in the context of urban planning and transport improvement (Lenntorp, 1999). The goal is to “make room and give leeway for various possibilities of action within city-regions” (Lenntorp, 1978) Space-time accessibility measures as “person-based accessibility” (Miller, 2007) developed under geocomputation largely based on Lenntorp formulation (Kwan, 2004a). Note: Activity programme and the ability to understand joint travel has a close relation to operational research. For example, applied algorithm for ridesharing (Wang, Kutadinata and Winter, 2016)
2. to understand the implications on the likely movements of people from changes in alternative urban scenarios	Analytical constructs in the urban scale mainly aimed at urban design for ex-ante analysis of spatial layout/configuration to suggest likely movement pattern and pattern in use of space e.g. likely concentration of shops	Scenario analysis and sketch planning approach. Generally, relies on the free parameters within developed model to be transferable between different context where data is not available.	Analytical constructs developed to aid understanding of the implications of changes in the urban environment on daily activity programme e.g. HATS (Jones, 1983)
3. to investigate movements of people in urban areas in an existing context based on the underlying assumed mechanisms/determinant of movements towards a model of future movements of people	Further development of analytical constructs in spatial representation and alternative distance measures. Testing new constructs against other representation and measures within space syntax for the same phenomenon.	Further development of analytical constructs in the form of new models with different approaches. First clear distinction is from four step models to activity-based approaches. There are multiple ways in which activity-based approaches is being developed centred around the generation of activity patterns. (Timmermans,	Development of analytical constructs that relates movement of people to space and time usually at a daily timeframe. One key feature is the concept of individual/household activities organised within a 24 hours period and how they can be performed within an urban environment including opportunities of activity participation and transport systems. Informed activity-

		Arentze and C.-H. Joh, 2002b)	based approaches in travel analysis in particular generation of activity patterns.
	Quantitative statistical analysis	Quantitative statistical analysis typically back testing model outputs to out of sample data	Descriptive statistics framed around qualitative concepts drawing the relationship between the ability to perform activity programmes in an urban context
4. to study a topic related to movement of people in an existing urban context from past/collected data	Data collection of observable movement patterns statistical correlation with space syntax metrics (and distribution of land use activities) Hiller et al (1993) theory of natural movement suggests the layout configuration is the primary generator of movement patterns	At the macro four-step model end, typically analysis of travel to work data as flow between transport analysis zones (TAZ) movement between zones conceptualised as “spatial interaction”. At the micro level, activity-based approaches analyses detail travel diaries as an analysis to model process towards the generation of activity patterns. Mode choice models typically follows a discrete choice analysis-model process. Data collection includes revealed preference (RP) and stated preference (SP) survey. Alternative within activity-based approaches make use of transition probabilities from existing sequential data – very high data requirement.	Data collection of travel diaries, primary or secondary. To study opportunities for mode changes given urban environment and travel diaries of residents in Zoetermeer (Dijst, de Jong and van Eck, 2002) To study public travel possibilities in the city of Karlstad given urban environment from a citizen/user perspective (Lenntorp, 1978). A more recent approach joint activity participation within space and time. (Neutens, Versichele and Schwanen, 2010) Related studies given recent improvements in related data includes possibilities in adding semantics to GPS data (Miller, 2017a) Supports choice set formation (related to mode choice models) (Chen and Kwan, 2012)

Table 14: Overview of the four general ways in which analytical constructs is used in research related to potential travel activities in alternative urban conditions (author’s own)

3.3.2 Part 2: The relationship between computational analytical construct for transport-integrated city design towards transport/travel related sustainability

Relevant concepts related to different notions of transport/travel sustainability	**Space syntax approach**	**Spatial science approach (Transport/travel demand)**	**Space-time approach (Space-time model)**
Transport activity (the amount of transport activity by mode is associated to GHG emissions)	Produces patterns of vehicular distribution and relative intensity	Produces estimate of transport activity at two points (1) modal split depending on the mode choice model chosen and (2) vkm of vehicles at the point of estimating traffic across a transport network in micro variations	Not directly applicable – travel and possibilities oriented but with explicit connection to passenger transport as comparison to personal travel modes in a given situation.
Travel activity	Produces patterns of pedestrian distribution and relative intensity	Modal split estimated at the point of mode choice model. No pedestrian variations of "traffic assignment" to street network	Possibilities of conducting an activity programme with different travel modes given an activity programme and urban environment; analysis applied across an urban area produce patterns of areas where activity programme with different travel modes can or cannot be performed
Multiple transport options	Limited	Typically expressed in the form of mode choice model and associated analysis.	Opportunity for travel modes
Space and experience for non-motorised modes	To some extent identifies pattern of pedestrian density "place structure"	Not directly applicable	Not directly applicable
Different notions of accessibility	Topological accessibility as spatial integration based on topological/angular distances	Not directly applicable; Hansen's gravity-based accessibility not related to TDM but related to LUTI	Person-based space-time accessibility
public participation	Not directly applicable	Scenario analysis	Possible public participatory approach shown in fundamental research related to analytical constructs

Table 15. summary of unit of analysis between three lines of research in relation to different notions of transport/travel sustainability

3.4 Theoretical framework for a space time analytical construct

3.4.1 Overview

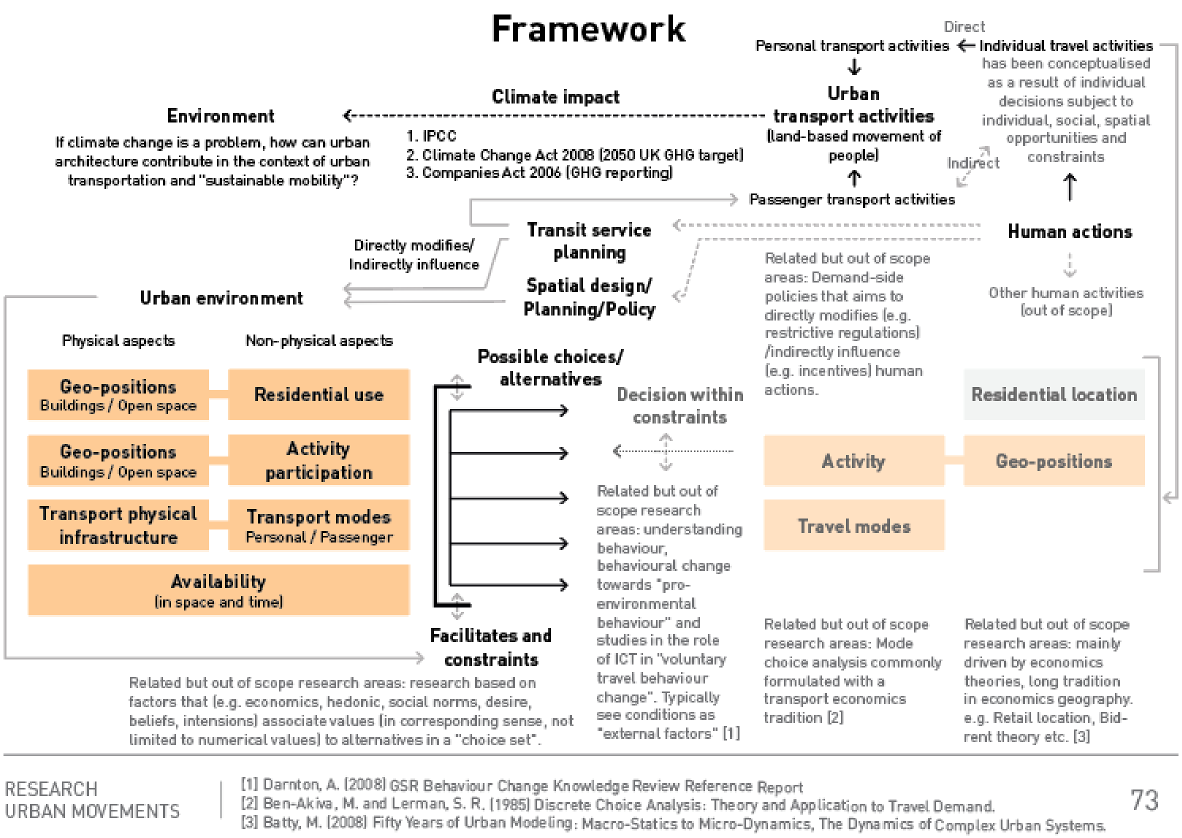

Figure 25 Theoretical framework to construct a computation-enabled analytical framework for transport-integrated city design

The theoretical framework sets out the relationships between alternative urban condition and daily activity programmes where different travel modes can be examined from an inhabitants' perspective.

A space time approach is adopted in this study for the development of the underlying construct to support the development of the analytical framework for the analysis of alternative urban condition. This study has an emphasis on the analysis of implications due to reconfiguration of spatial functions and reconfiguration of passenger transport services. These are understood as facilitating and constraining spatio-temporal conditions to which inhabitants' daily activity programmes involving traversal of physical space can or cannot be performed.

3.4.2 Why space time model?

The specific type of space time model of interest has been used to investigate alternative urban conditions. The space time models are designed to simulate the number of combinations of urban opportunities accessible to conduct a complex chain of location-bound activities within an individual's space and time constraints. (Lenntorp, 1978; Ritsema van Eck, Burghouwt and Dijst, 2005)

Previous work from Lenntorp and Dijst, enables the consideration of both a spatio-temporal and an environmental perspective. Space time model enables the investigation and analysis of alternative urban conditions. Lenntorp's PESASP is a space time model developed (Lenntorp, 1976) and applied in studies of travel modes possibilities in the city of Karlstad (Lenntorp, 1978) and the city of Orebro (Lenntorp, 1979). Dijst's MASTIC (Dijst, 1995) was developed in 1995 and subsequently applied in the study of mode change opportunities (Dijst, de Jong and van Eck, 2002) and explorative simulation study of spatial configuration in the city of Zoetemeer (Ritsema van Eck, Burghouwt and Dijst, 2005).

The space time model PESASP by Lenntorp (Lenntorp, 1976, 1978) is widely cited in activity-based approach to travel analysis in the transport modelling field of study (Ettema and Timmermans, 1997) and space time accessibility (Kwan, 2004a). The space time model is not publicly available and that it can only be found in article description, the Lenntorp's space time model approach is a significant analytical construct to revisit and as a simulative variation of time geographic construct for alternative urban condition. PESASP is not publicly available.

The development of the space time model in this study as an operational model to support the analytical framework (to support considerations in sustainable travel activities for transport-integrated city design) within this thesis (1) adopts concepts from PESASP through the diagrams and description by Thrift (Thrift, 1977), Pickup and Town (Pickup and Town, 1981), Jones (Jones, 1983) and Kwan (Kwan, 2004a) (2) extends the procedures using contemporary methods informed by the trend in the subsequent developments of space time model for analysis of existing conditions for empirical studies.

3.4.3 Why develop space time model in this study?

Simulative space time models are currently limited in their ability to work with detailed transport network and time-sensitive passenger transport. It is therefore not directly applicable to investigate time-sensitive passenger transport within transport-integrated city design. It is an opportunity for this study to address this gap in enhance the missing aspects, especially to include the ability to investigate time-sensitive passenger transport services in alternative urban conditions for transport-integrated city design.

3.4.4 How does a space time model work?

Simulative space time models are designed to simulate the number of combinations of urban opportunities accessible to conduct a complex chain of location-bound activities within an individual's space and time constraints. The number of combinations of urban opportunities differs by travel modes. (Lenntorp, 1978; Ritsema van Eck, Burghouwt and Dijst, 2005) This number of combinations can be viewed from a specific urban opportunities or the whole urban condition within the model. As a basic example, if one has to go to work from 9:00am to 5:30pm and go to a shop after work, looking at the overall urban condition - how many combinations of workplace, shop and residential location can this be performed in an urban condition with a set of spatially distrubuted workplaces, shops and residential locations? With the same example looking at the a specific workplace - how many combinations of shop and residential location can this be performed in an urban condition with a set of spatially distrubuted shops and residential locations.

A space time model of this type requires the information of the types of urban opportunities with spatio-temporal constraints, the travel time required to travel between urban opportunities and a daily activity programme of an individual which includes the spatial and temporal constraint expressed the need to conduct a certain type of location-bound activity at a certain time of day.

The four interacting elements of transport network, transport services, urban opportunities (residential locations, workplace, shops etc) and daily activity programme of an individual contributes to the different number of combinations of urban opportunities accessible by an individual and in alternative urban conditions where one or more elements are reconfigured.

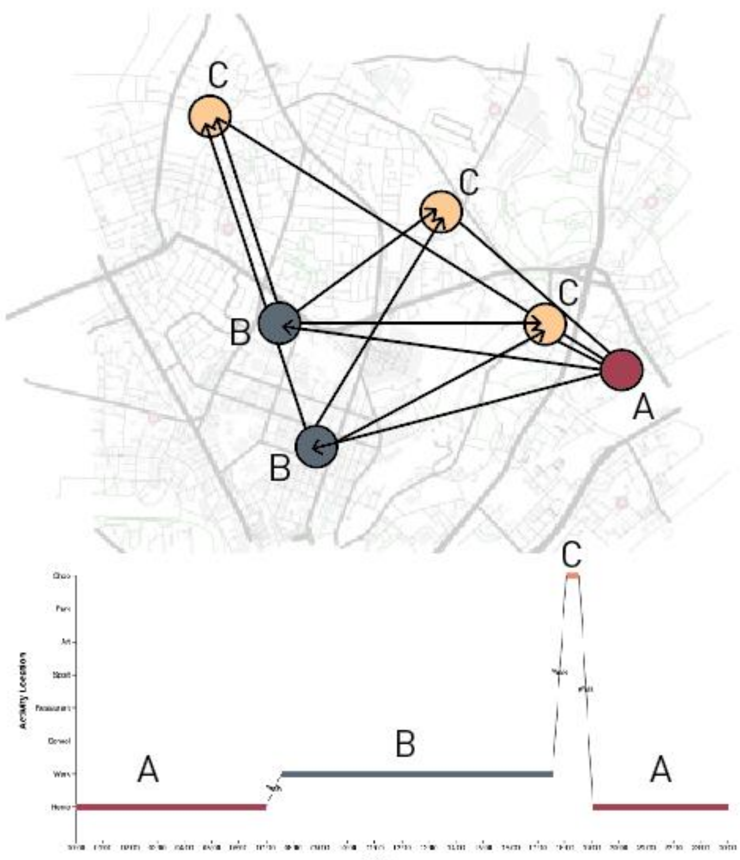

Figure 26 An example of urban condition (above) and activity programme (below), whiel the image shows all the possibilities of combinations, some of which cannot be conducted due to the space and time constraints. An algorithmic process is used to determine whether the different combinations of A-B-C-A that are possible within the constraints.

An algorithmic process as part of the space time model takes the input of a daily activity programme and the urban condition, computes the number of spatio-temporal opportunities accessible to conduct a complex chain of location-bound activities. For example, if one has to bring a child to a school before work that starts at a specific time and bring the child home at a specific time after work, what are the possible combinations of residential location, workplace and school that can satisfy the time requirements? In order to arrive at the location at the right time, certain opportunities of workplace and school in combination are difficult to reach by certain travel modes within the space and time constraints.

3.4.5 The underlying presumptions and theoretical constructs supporting space time models

	Description	
Presumptions	Presumptions of human condition under an early time geography framework	**Space as a scarce resource** Indivisibility of human beings and many other entities, living and non-living. Limited packing capacity of space **Time as a scares resource** Limited length of each human life The fact that every task has a duration The limited ability of human beings to take part in more than one task at a time (note: this assumption has evolved in development of studies in sequences of multiple activities (Ellegard, 2018)) Movement between points in space consumes time Every situation is inevitably rooted in past situations Hagerstrand, 1975 (Pred, 1977; Thrift, 1977)
Theoretical constructs	Abstract concepts and entities	Activity programme describes the spatial temporal constraints to participate in location-bound activity at specific time of day and duration. Opportunities for activity participation (OAP) are urban opportunities such as residences, workplace, schools and other amenities and facilities. Early work emphasis on time sensitive attributes such as opening hours of services such as nurseries, banks, library, post office and shops.
Theory	Set of propositions expressing relationships between concepts and entities	Possible combinations of OAP given an activity programme (Lenntorp, 1978; Dijst et al, 2002) The number of possible combinations opportunities accessible to conduct a complex chain of location-bound activities. This can be from a specific urban opportunity or the whole urban condition within the model.
Model	Operational set of propositions expressing	Possibility to travel between opportunities support by different travel modes (further developed in this study)

	relationships between concepts and entities	The possibility to reach an opportunity before a given time to conduct a location-bound activity (further developed in this study)
Method	set of steps used to perform a task (algorithms)	Computation of possible combinations of opportunities for activity participation (further developed in this study)
Instantiation	"the realisation of artefact in its environment"	Analytical framework to produce outputs suitable for interpretation and comparison of travel modes possibilities to support sustainable travel activities (developed in this study)

Table 16. Relevant theories and conceptualisations adopted and developed through the development of the analytical construct with two parts. Part 1: Analytical framework (instantiation), Part 2: Underlying space time model (Presumptions, theoretical constructs, theory, model, method)

3.4.6 What are being extended and developed through this study?

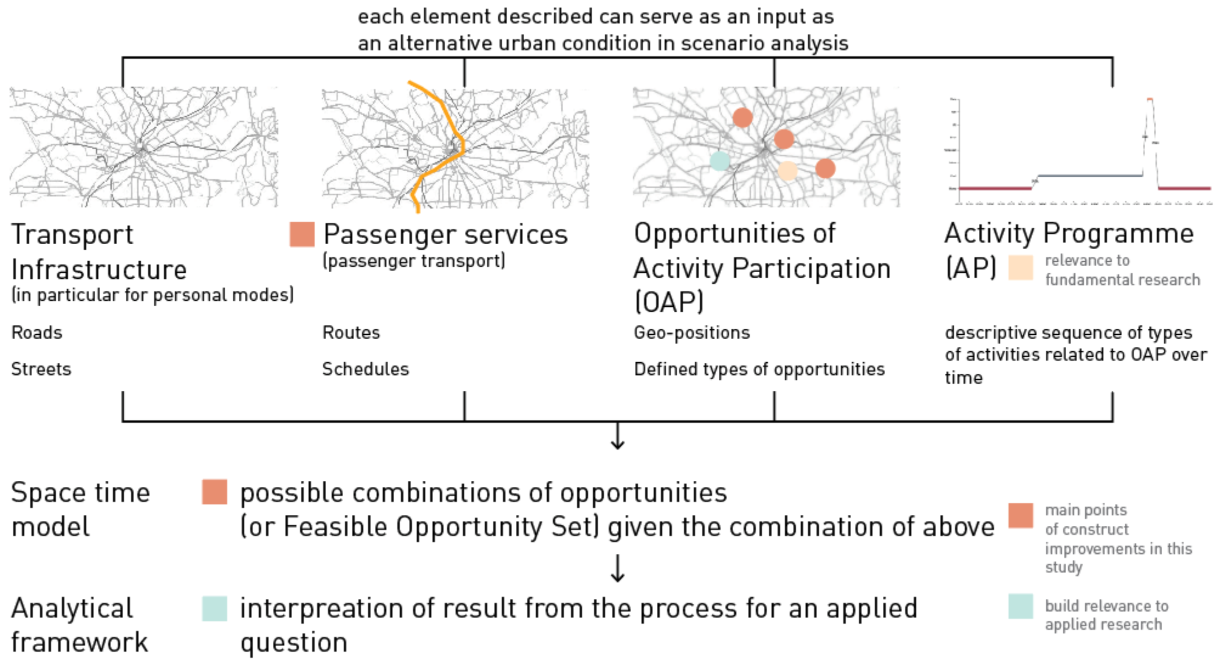

Figure 27 The relationship between alternative urban conditions, what can be reconfigured in an alternative urban condition, space time model and analytical framework developed in this study

This study adopts the theoretical constructs to develop a new space time model with specific enhancement in the steps to compute travel time required to travel between urban opportunities. In particular, the to incorporate time-sensitive passenger services and the ability to consider a time-sensitive passenger services in alternative urban conditions which was not previously possible.

A detailed account of time-sensitive passenger services differs from a route-based description of passenger transport. A person cannot travel on a bus at any point in time because a bus route exists. The frequencies and timings of the bus service is important. A service-based description of passenger transport meant that the individual’s spatial and temporal constraint and the availability of public transport at the specific time frame where travel is needed is taken into consideration.

Chapter 4 - Research design and Methodological considerations

4.1 Introduction

4.1.1 Why constructive research?

The choice made in this study to adopt a constructive research framework relates to the research motivation and the research topic. The research motivation with a domain-specific need for city design tends towards applied studies but the research topic of potential transport and travel activities in alternative urban conditions tends towards theories and conceptualisations from fundamental research. As identified in previous chapters, there are multiple conceptualisations in fundamental research for this topic in academic literature.

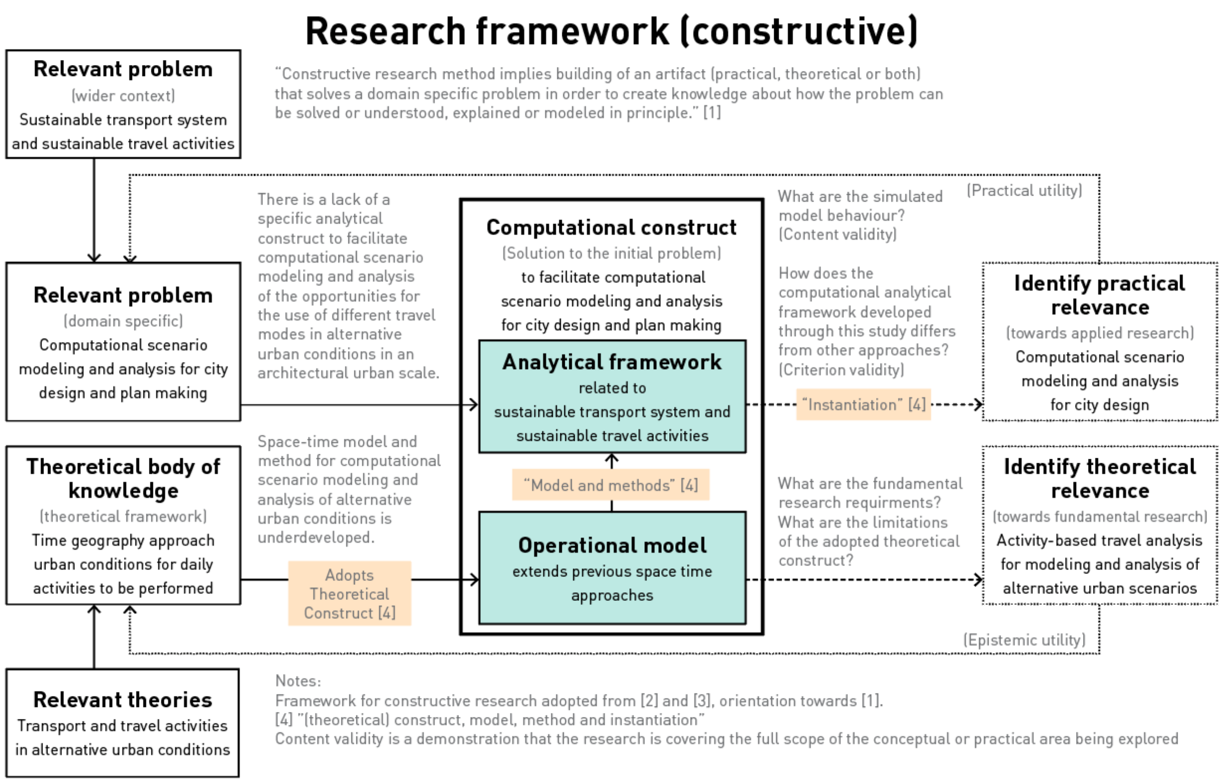

Figure 28 Framework for constructive research methodology towards info-computational knowledge generation, a combination of Dodig-Crnkovic (2014) view on "computational models and simulations" as constructive research and Kasanen and Lukka (1993) CRA framework for practical and theoretical relevance

A constructive research methodology allows the development of new methods, tools and techniques aimed at applicability beyond a single case study. It is a research process enabling the production of innovative constructions intended to contribute to a wider relevant problem (such as climate change) and to address domain-specific needs (the need to understand the implications of alternative urban conditions in city design) and in so doing make a contribution to theory.

4.1.1.1 Domain-specific relevant problem

In this study, the relevant domain-specific practical problem is the lack of a specific analytical construct to assist in the interpretations of implications to accessibility by different travel modes towards transport/travel related sustainability with new urban developments and new transport services in alternative urban conditions for transport-integrated city design.

For transport-integrated city design to engage with prospective space and time-sensitive passenger transport services as part of future spatial changes, there is a need to include passenger transport as well as the spatial distribution of facilities and spatial functions, transport infrastructure to analyse and understand the opportunities and constraints from the urban environment to daily activities of inhabitants.

The research need identified in previous chapters: There is a lack of appropriate computational analytical constructs in architecture for the modelling and analysis of opportunities for the use of travel modes in alternative urban condition.

4.1.1.2 Theoretical body of knowledge

This study draws on space time approach and the associated theoretical constructs from time geography for the development of the underlying space time model to support the analytical framework.

The research gap identified in previous chapters: Space time models to facilitate the analysis and assessment of alternative urban conditions are underdeveloped.

4.2 Research design

The research design section describes how the research outcomes will be obtained in line with research objectives in relation to the research questions. Followed by a section on methodological considerations.

The research outcome is a computational analytical construct developed through this study. The computational analytical construct includes the development of a computation-enabled analytical framework to address the domain-specific need and the development of a space time model that supports the analytical framework to address the research gap.

In order to develop the underlying space time model (see section 3.4 pg138-143 on the definition of the specific type of space time model, what it does and how it operates), there is a need to construct an operational digital model and associated algorithmic procedures (see next chapter for details) extending previous space-time model approaches with specific attention on the ability to examine alternative urban conditions that can be explored for transport-integrated city design. This include the ability for a digital model to be reconfigured with the inputs of the opportunities of activity participation, transport infrastructure and time-sensitive passenger services.

Simulative space time models are designed to simulate the number of combinations of urban opportunities accessible to conduct a complex chain of location-bound activities within an individual's space and time constraints. The number of combinations of urban opportunities differs by travel modes.

In order to develop the analytical framework, there is a need to develop a way of understanding the number of combinations of urban opportunities accessible to conduct a complex chain of location-bound activities within an individual's space and time constraints and to visualise the differences in the ability to use different types of travel modes.

4.2.1 Research aim

The aim of this study is to develop a computation enabled analytical construct as a method to facilitate diagnostic assessment of alternative urban conditions for transport-integrated city design. The process taken to develop the analytical construct and the analysis of the analytical construct developed aims to the identify implications for applied research towards practical utility and implications for fundamental research towards epistemic utility.

4.2.2 Research objectives and steps in a constructive research approach

This study adopts a constructive research framework as a research guide to the construction of the computational analytical construct. "Constructive research method implies building of an artifact (practical, theoretical or both) that solves a domain specific problem in order to create knowledge about how the problem can be solved or understood, explained or modelled in principle." (Dodig-Crnkovic, 2014)

The table below shows the steps in a constructive research approach aligned with **research objectives** in this study and the relevant sections within the thesis.

CRA steps	Objectives	Relevant sections
Find a practically relevant problem that also has research potential	Conduct literature review on current approaches to GHG emissions reduction in transport	Background: Climate change and transport Problem in the wider context: sustainable transport system and sustainable travel activities
	Conduct literature review on current approaches in city design towards sustainable transport system and to support sustainable travel activities	Background: City design Domain-specific problem: Current analytical approaches are limited to facilitate computational scenario modeling and analysis for city design
Obtain a general and comprehensive understanding of the topic	Conduct an overview literature review on how travel behaviour is conceptualised	Overview of literature on travel behaviour

	Conduct state-of-the-art review on current computational analytical constructs for the modeling of potential transport and travel activities in alternative urban conditions	State-of-the-art review
	Analyse analytical approaches and their associated theoretical frameworks related to future transport and travel activities	Comparison of three analytical approaches: metrics of urban characteristics, transport modelling and space time approach
	Define theoretical framework and theoretical contributions for this study	Theoretical framework
Innovate (i.e. construct a solution idea)	Construct an operational digital model and methods extending previous space-time model approaches with specific attention to the ability to examine alternative urban conditions	Operational model: design and implementation
	To develop digital model for the inputs of the opportunities of activity participation, transport infrastructure and time-sensitive passenger services	Constructing urban conditions
Demonstrate that the solution works	Test the structure and model behaviour of the analytical construct through multiple scenarios (demonstrate construct effectiveness)	Case study experiments • Interpretation of results
Show the theoretical connections and the research contribution of the solution	Provide evidence of criterion-based validity	Criterion-based validity • Construct convergent validity • Construct discriminant validity
Examine the scope of applicability of the solution	Interpretation of results from case study experiments drawing connections to the literature	Discussion • Implications for applied research related to transport-integrated city design • Implications for fundamental research related to the analytical approach

Table 17. Steps in constructive research approach informed by Kasanen and Lukka (Kasanen and Lukka, 1993, p. 246) with author's own relevant sections identified in this study.

4.2.3 Research questions

Primary questions related to the analytical construct to be developed in this study:

1. How can space-time model be extended incorporating new technologies and data sources for ex-ante (before the fact) analysis of alternative urban conditions?

2. How can a space-time computation-enabled analytical construct facilitate scenario modelling and diagnostic assessment of alternative urban conditions toward sustainable transport systems and to support sustainable travel activities?

Secondary questions related to the background knowledge and review to support the development of the analytical construct:

3. What is the current available knowledge about transport-integrated city design toward sustainable transport systems and to support sustainable travel activities?

    a. How is GHG emissions reduction in urban transport conceptualised?
    b. What are the current approaches to GHG emissions reduction in urban transport?
    c. How can city design contribute to sustainable transport systems and to support sustainable travel activities?

4. What are the theoretical knowledge and considerations to support an appropriate computational analytical construct for ex-ante analysis of alternative urban conditions towards sustainable transport systems and support sustainable travel activities?

    a. What are known conceptualisations of transport and travel analysis in academic literature? (literature review Chapter 2 section 1)
    b. What are the analytical approaches to facilitate scenario modelling and diagnostic assessment of alternative urban conditions? (literature review Chapter 2 section 2)
    c. How do the analytical approaches relate to notions of transport/travel-related sustainability? (literature review synthesis and conclusion)

4.2.4 Design evaluation criteria

There are two parts to the analytical construct developed in this study.

The first is an analytical framework for the comparison between opportunities for travel modes. The design evaluation criteria for the analytical framework are defined based on Hevner et. al. (2004) guidelines to design evaluation methods to “construct detailed scenarios around the artefact to demonstrate its utility”.

While it is beneficial to evaluate the computation enabled analytical framework in terms of its fit of purpose to assess the usefulness of the construct in a city design process, the validity of the analytical framework relies on the validity of the underlying computational model and method.

The second is the underlying model and methods that supports the analytical framework. Two types of criterion-based construct validity are sought in this study. The first is to compare with construct known to be similar for construct convergent validity and the second to compare with construct known to be different for construct discriminant validity.

For construct convergent validity the space time model developed in this study is compared against PESASP (Lenntorp, 1978) to test for its similarity. For construct discriminant validity the model is tested against cumulative opportunity measure (Guy, 1983) as a common accessibility measure but known to be dissimilar (Kwan, 1998).

4.3 Methodological considerations

As mentioned in previous section 1.2 pg26, city design involves proposal of plans that indirectly and directly alter urban conditions. Karimi (2012) argues that the design process can be supported by an analytical framework that enables a diagnostic assessment of alternative designs towards desirable goals in the wider context. (see section 1.5 pg59)

- city design produces and develops proposals that contain alternative urban conditions
- knowing what can be known in alternative urban conditions is important to improving alternative urban conditions

The scope of this study focuses on a desirable goal in the wider context relating to sustainable transport systems and sustainable travel activities.

The identified domain-specific problem is the lack of appropriate computational analytical constructs for the modelling and analysis of opportunities for the use of travel modes to conduct daily activities in alternative urban conditions. The consideration of multiple transport modes within transport systems to support more sustainable travel activities is an important aspect in the wider context (Litman and Burwell, 2006). The modelling and analysis of transport and travel activities is an important aspect in the understanding of cities (Timmermans, Arentze and C. Joh, 2002).

While there are existing analytical constructs including model and methods for the simulation and analysis of transport systems and travel activities under different urban conditions, they are limited for two reasons (1) limited analytical constructs applicable for the purpose stated above (2) there are limited analytical constructs that are applicable for city design at an urban architectural scale.

The consideration of passenger transport in the way that they connect different parts of a city enabling location-bound daily activities is absent from current analytical approaches in architectural city design. The analytical approaches in the wider research context of land use transport integrated modelling and analysis considers the connections between different parts of a city. However, the spatial unit based on zones or grids and the dominant economic-oriented approach has limited applicability for the research topic in this study for transport-integrated city design at the scale of local developments.

The need for development of an appropriate computational analytical construct in this context is paramount. The development of a computational analytical constructs is inherently constructive (Dodig-Crnkovic, 2014). Design science research (DSR) (March and Smith, 1995; Hevner *et al.*, 2004) and constructive research approach (CRA) (Kasanen and Lukka, 1993) are two interrelated research approaches in research that consider artificial constructs as research outputs.

This study adopts a constructive research framework as an overarching framework for the construction and analysis of a computational analytical construct. A constructive research framework involves the development of an artificial construct to solve a relevant domain-specific problem. In this case the lack of an appropriate analytical construct to model, analyse and assess opportunities for the use of travel mode in alternative urban conditions in an architectural context for transport-integrated city design.

This study aims to contribute to practical and theoretical knowledge through the development of a computational analytical construct. This study focuses on the evaluation of the developed computational analytical construct as a research output. Face, content and criterion-based validity are three known types of construct validity relevant for the evaluation of constructs. This study provides evidence for content and criterion-based validity.

The specification of the computational analytical construct is documented to provide evidence that it includes the variables of interest and allows for repeatability by other researchers to support content validity. Systematic case study experiments are conducted with the computational analytical construct to describe and test the underlying model structure and model behaviour.

The computational analytical construct is evaluated against two types of criterion-based validity, namely convergent validity and discriminant validity. Convergent validity tests for similarities in similar constructs and discriminant validity tests for differences in constructs for a similar purpose. Finally, the implications of the computational analytical construct for applied research and fundamental research are identified and described.

4.3.1 Applied and fundamental research

In a planning research context, “applied research” is “driven by practical aims and is conducted in practice for purposes of offering practical solutions to concrete problems”, “fundamental research” is “driven by theoretical aims and is conducted in academia for purposes of advancing fundamental knowledge about planning and the world that planning deals with” (Barry, 2014, p. 62). It is also acknowledged that research in this field is typically not purely applied or purely fundamental but somewhere along the applied-fundamental continuum.

Fundamental research is motivated by knowledge gaps in a phenomenon of interest and its research findings are aimed at generating knowledge of the phenomenon of interest with a focus on theory testing and building. The goal of applied research is to fulfil a domain-specific need. Findings from applied research are aimed at immediate practical implications focusing on problem solving (Andranovich and Riposa, 2011). In fundamental research, the development of constructs is primarily focused on their use for empirical studies of real-world phenomena, whereas applied research uses and applies knowledge from multiple sources including knowledge from fundamental research.

4.3.2 The problem of design research for future travel activities

The domain-specific problem is intrinsically about prospective urban conditions that are not yet realised in the real world. From a design research perspective, the knowledge required is viewed as “design-relevant explanatory/predictive theories” (Kuechler and Vaishnavi, 2012). It is important to acknowledge the complexity of forecasting future travel activities, which has been an ongoing fundamental research topic (Miller, 2014). There are known advancements in transport modelling of travel activities including TASHA (Miller and Roorda, 2003) and ALBATROSS (Arentze Theo A.andTimmermans, 2000) related to the generation of activity patterns in the recent area of activity-based travel analysis in transport modelling. The gap between transport modelling and urban architecture persists.

The specific problem within the wider problem of sustainable transport system and travel activities relates to the conflicting role of passenger transport in supporting more sustainable travel activities while the operation of passenger transport services has an environmental impact.

The adaptation of fundamental research methods from transport modelling is not an easy task because the type of data generated from city design does not match with data inputs of fundamental research methods. The main difficulties are the differences in space and people-related units incorporated in models and by extension its underlying theories and conceptualisations.

One of the main difficulties in the attempt to apply well known methods from land use transport integrated (LUTI) modelling in city design is the unit of space. LUTI models are regional in scale, in other words, the unit of the “land” component is highly simplified and lacks the fidelity to represent the elements in a city design scale including urban blocks, plot and dwelling unit (Krehl *et al.*, 2016).

As pointed out from previous literature reviews on LUTI (Iacono, Levinson and El-Geneidy, 2008), there has been a shift towards micro units that attempts to represent the parts within models in greater resolution. This is in line with the more recent modelling approaches of agent-based modelling that attempts to simulate interactions of actors rather than interactions of factors (Macy and Willer, 2002), thus the increasing the capacity of fundamental research in research questions related to complexity (Crooks, Patel and Wise, 2014). The majority of the academic effect has been placed in the areas of the representation of people. As identified in the state-of-the-art review, the most recent methods in travel analysis typically aim at behavioural studies, the underlying connection to urban conditions that facilitate and constraint the alternative choices of travel mode and residential location is a potential for an urban architectural contribution to the topic.

4.3.3 The problem of methodological development for fundamental research in applied research

The research gap identified relates to methodological development for fundamental research on the interactions between urban conditions and travel activities.

Fundamental research of travel activities in relation to urban conditions as an urban phenomenon are retrospective. Research findings are a result of analysis of empirical data and collections of past data related to the urban phenomenon.

The types of data collected and the type of analysis depends on the theoretical approach adopted for the research. For example, a space syntax approach to test the hypotheses derived from the theory of natural movement would include the data collection of volume of pedestrians on a set of streets within the study area over a specific time period. The volume of pedestrian traffic is then quantitatively analysed against space syntax-based measures of the spatial configuration of the study area.

There are multiple formulations under behavioural approaches to travel activities. While there are multiple advanced fundamental research methods, a basic example relevant to this study is described as follows. This refers to the mode choice step in a four-step transport model (see chapter 2 for a description). The mode choice step is formulated as mode choice model. A mode choice model includes a utility function. A utility function includes a number of variables and their coefficient as free parameters that are adjusted by empirical data for analysis. A study based on the basic behavioural approach described above involves data collection of individuals' attributes corresponding to factors included in the theoretical approach, typically in terms of travel time and cost. Travel time and cost corresponds to two concepts from economics - "value of travel time (VTT)" and "willingness-to-pay (WTP)" respectively. The data is then inserted into a formulation of mode choice model which includes a utility function that contains the specification of factors included in the theoretical approach. The mode choice model produces the probability of choosing a travel mode included in the model as alternative choices, which is interpreted through probability distribution as modal split of different travel modes. Validity of a mode choice model is determined by comparing the model outputs and empirical data of modal split in a given context.

As Andranovich and Riposa (2011) point out, applied and fundamental research are not mutually exclusive. Applied-oriented urban research that makes use of methods from fundamental research can identify practical implications of conducting fundamental research (Andranovich and Riposa, 2011). Models and methods developed from fundamental-oriented urban research in land use and transport - while their main role is on theory building for “a better understanding of cities” (Batty, 2008b) - often draw implications on conducting applied research. This study targets the development of a method to facilitate research where the applied and fundamental converges. This study attempts to identify the implications of the developed method in applied and fundamental research through the developed method to facilitate research.

This study is positioned in the fundamental-applied continuum through the development of an analytical construct in two interrelated parts:

Part 1 consists of a computation enabled analytical framework to facilitate sense making and understanding. It is developed as a potential solution to the domain-specific problem of comparison different travel modes under alternative urban conditions.

Part 2 consists of the development of the underlying operational model including the computational model, methods and algorithmic procedures. A computational model and method connect theoretical constructs to what can be known about the potential travel activities in alternative urban conditions. The operational model in this study is based on and extends space time models.

4.3.4 Customisations made to constructive research framework for this study

The constructive research framework in this study draws upon (1) Dodig-Crnkovic (2014) fundamental research-oriented constructive research towards info-computational knowledge generation, applied research oriented guides to constructive research (2.1) Kasanen and Lukka (1993) constructive research approach and (2.2) Hevner et. al. (2004) March and Smith (1995) on information system design research. These frameworks for research were conceived for different purposes compared to this study, relevant elements from each framework are adopted into this study.

The context of this study, the development of appropriate computational analytical constructs for the urban phenomenon of transport and travel activities in alternative urban conditions points to the development of computational models and simulation methods. This is supported by Dodig-Crnkovic’s (2014) view of computational models and simulations as constructive research for knowledge generation.

There are two major applied research-oriented frameworks to constructive research (1) design science research DSR and (2) constructive research approach CRA. Design science research most discussed in information system design research (March and Smith, 1995; Hevner *et al.*, 2004) offers research guidance on computational constructs and identifies four main types of research outputs. The first known formulation and discussions of constructive research framework (Kasanen and Lukka, 1993) revolve around the research on project management and accounting where it was first developed and it is not specific to computational constructs.

Both applied research-oriented frameworks refer to "artifacts" as artificial constructions within a study as supposed to socially constructed phenomena. Artifacts in CRA includes "all human made artefacts, such as models, charts, plans, action plans and strategies, organizational structures, commercial products, and information systems" and DSR includes "constructs, models, methods or instantiations". This study adopts the term "constructions" when referring to artifacts produced as research outputs (Piirainen and Gonzalez, 2014).

This study adopts the views of Winter (2008), March and Smith (March and Smith, 1995) from information system-oriented design research as a useful framework to facilitate the description and understanding of different elements within computational constructions. How it relates to application and how an artificial construction makes use of existing theories of urban phenomenon.

"Construct, model, method and instantiation" (March and Smith, 1995) are four well-known types of research outputs as artificial constructions from constructive-oriented research. Construct, in the sense of theoretical construct, forms the "vocabulary of a domain" and "conceptualisation used to describe problems within the domain and to specify their solutions". This includes the presumptions, conceptualisations and entities to be included. Model consists of an operational set of propositions expressing relationships between conceptualisations and entities. Method refers to a set of steps used to perform a task, for example, algorithms. Instantiation is defined as "the realisation of artefact in its environment" (March and Smith, 1995). Artificial constructions make use of "kernel theories" that are theories from design, natural or social sciences (Hevner and Chatterjee, 2010).

Chapter 5 - Construct implementation and interpretation of results

5.1 Introduction

There are two parts in the computational analytical construct that is developed in this study. (1) the development of a computational enabled analytical framework that relates the results from a space time model developed in this study to the wider problems of travel mode opportunities in alternative urban conditions and (2) the development of the underlying computational space time model that relates the space and time constraints of individuals activities and the urban opportunities.

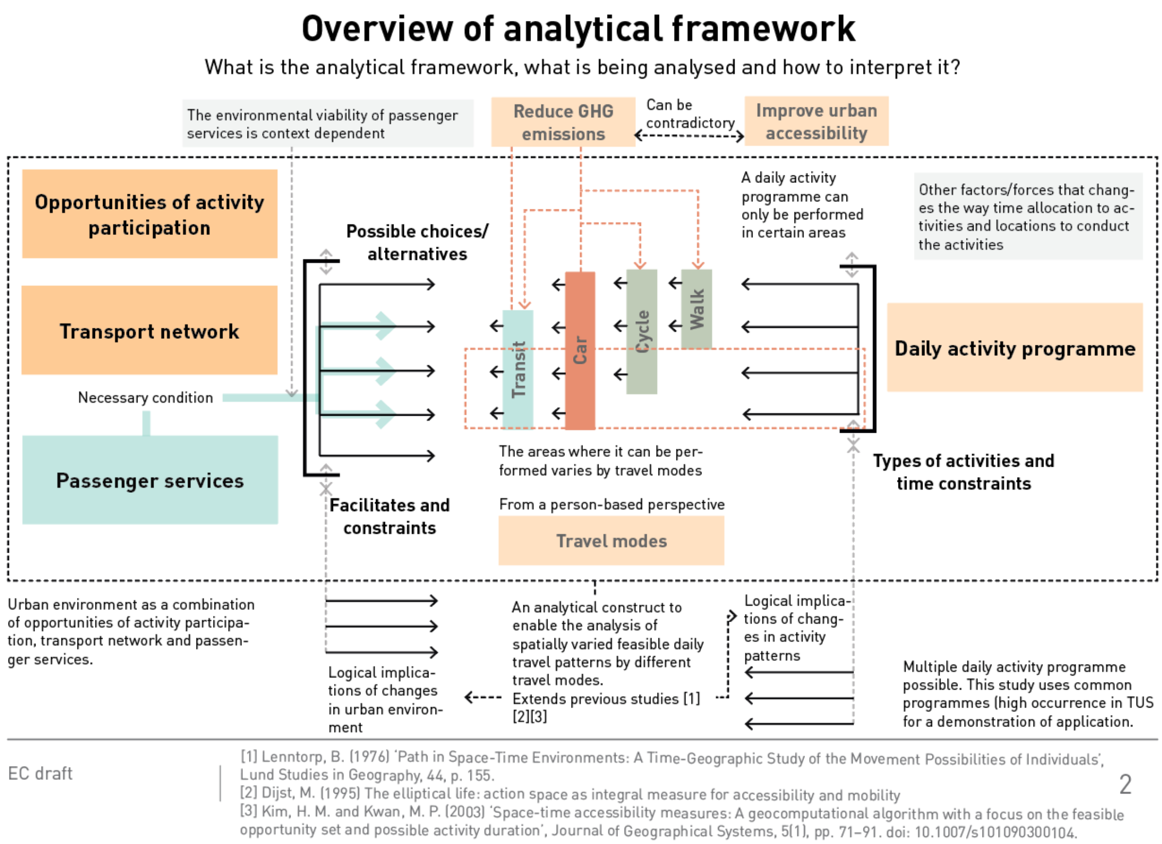

Figure 29 overview of analytical framework for the interpretation of the results towards sustainable transport system and to support sustainable travel activities from the computational space time model both developed in this study

The underlying space time model to explore alternative urban conditions is adopted and extended based on the work by Lenntorp PESASP (Lenntorp, 1978) for the underlying space time model in this study. PESASP is not publicly available, the operational model constructed within this thesis (1) adopts concepts from PESASP through the diagrams and description by Thrift (Thrift, 1977), Pickup and Town (Pickup and Town, 1981), Jones (Jones, 1983) and Kwan (Kwan, 2004a) (2) extends the procedures using contemporary methods informed by the trend in the subsequent developments of space time model for analysis of existing conditions for empirical studies.

The structure of this chapter begins with the first section describing the detail and rationale in the design and implementation of the underlying operational model that produces outputs to support the analytical framework. The second section explores the properties of the analytical construct through case study experiments and demonstrates its use. The third section evaluates the analytical construct. The fourth section with a discussion aims at critical assessment and reflection on the study. The fifth section on further work. Finally, the sixth section concludes with a summary of contribution to knowledge and the research outcomes.

5.2 Operational model: design and implementation

5.2.1 Design considerations

The analytical construct contains four main elements as variables that are designed to be modified, each with its own requirements as a digital model in terms of specification of data to facilitate the algorithmic process that is required for the computation of possible combinations of urban opportunities accessible given space and time constraints of the individual, transport services and urban opportunities.

1. **Geo-positions of different types of opportunities for activity participation** includes residential, work place, sports facilities, shops. Types informed by data source for activity programmes.
2. **Transport infrastructure** including road, street and rail infrastructure
3. **Passenger service provisions** within a mix of other travel modes e.g. private cars, public transport, cycle and walk
4. **Daily activity programmes** (other related terms include: activity schedules, activity patterns, activity time sequence. Ellegard (2018) discussed the use of different terms in different context and how it has evolved from normative activity programmes to empirical studies of activity time sequences. Activity programmes is adopted in this study as it closely relates to the original term used in early space-time models such as PESASP)

5.2.2 Data considerations

There are two main secondary data sources for geographic data of built environment in a UK context. Geographic data can be sourced from Ordinary Survey or OpenStreetMap. Ordinary Survey data is limited to the UK originally although other countries are now available. It requires proprietary paid access. OpenStreetMap is a crowdsourced voluntary geographic information platform and is known to be used in the academic communities.

OpenStreetMap will be used for this study due to the wider availability of data in other countries which increase the study’s transferability to another situation and its previous use in academic communities.

Transport infrastructure

Transport infrastructure includes roads, street and public transport related infrastructure including stops/stations and routes. One of the requirements of this study is to understand travel time between locations given the spatial temporal constraints. In this sense, the transport system is **not only a visual representation** that contains the geometry of the transport network but requires the data to include **topologically linked structure and additional attributes** for example one way street and turn restrictions in a road-based network for analysis of travel time between any pair of locations under study through a routing algorithm.

Road and street network

There are two main sources for geographical data for roads and street networks. 1) Ordinance Survey 2) OpenStreetMap.

The official dataset in the UK is provided by Ordinance Survey (OS) that can be accessed through University of Edinburgh EDINA Digimap service through an educational institutional subscription or by commercial providers. The geographic data require license agreement depending on the type of data and use. OS provides a dataset named OS Mastermap Highways Network (originally OS Integrated Transport Network) that includes relevant data for routing purposes. Data format available through Digimap includes ESRI File Geodatabase (FDGB) for road and path network and Geography Markup Language GML3 for separate road network and path network. Ordinary Survey data is limited to the UK.

An alternative is OpenStreetMap (OSM). (Coast, 2004, 2007) OSM is an open collaborative voluntary geographic information platform where users are able to edit and contribute to the mapping dataset. (Haklay and Weber, 2008) OSM is known to be used in the academic communities especially in the urban studies and analysis of street networks (Boeing, 2017) and although there are scepticism in the quality in crowd sourced dataset, in certain use case such as a study in comparison between OSM and OS data for cycling, OSM “outperforms” the proprietary data approach such as the OS (Lovelace, 2014). OSM data is available in areas outside UK as well as within UK. The level of detail and data quality varies in different areas for example, in Manchester, UK not all buildings are included but it is something to be expected in crowdsourced data and the main data required is road and street network in this study.

Passenger transport service

There are two interrelated datasets for public transport networks (1) geometry data of routes and (2) public transport schedules with stations/stops.

Routes represented as geometry is not enough for routing purposes. Similar to the dataset for road and street networks, there are specific data requirements for a public transport network for routing purposes that enables the query of possible travel time between locations at specific time. Finding routes on schedule-based public transport network is more demanding than road and street based routing due to the fact that there can be interchanges between different routes and that the timing needs to match based on the scheduled level of services. There are also connections between a street network and the stations/stops for a “door-to-door” route.

For general routing and journey planning purposes, there are no requirements for geometry of the routes. One example of an application of a router as a tram journey planner where no geometry is represented is Tramchester by a company called ThoughtWorks. (Cartwright and Earlham, 2014) The results of a route from the journey planner consist of arrival time, departure time, stations for transfers. However, the geometry of the route is important in estimating climate impact from the vehicle kilometres travelled (VKM) or passenger kilometres travelled (PKM) (see section 1.4 on environmental sustainability pg35).

Some public transport network data in the UK can be found on UK Government open data portal. (Data.gov.uk, 2010) For example, bus routes as geometry shape files and train network as geometry shape files. UK nationwide scheduled public transport data is available through Association of Train Operating Companies ATOC for trains and bus/tram scheduled data is available through Traveline National Dataset. Transport for Greater Manchester (TfGM) publishes bus and tram schedules within the Greater Manchester region on the open data portal that is updated weekly.

Public transport schedules in a machine-readable format is not as widely available as geographic dataset. There are also different standards for the data format. In a UK context, these includes TransXchange for UK bus schedules, Association of Train Operating Companies ATOC-CIF (RJIS-CIF) and Association of Transport Co-ordinating Officers ATCO-CIF (Bus) Traveline/TransportDirect. There are common open specifications such as the General Transit Feed Specification GTFS for planned public transport data which has increased data availability in more cities in recent years.

GTFS for Greater Manchester containing bus and tram schedule data is used in parts of this study. (Data.gov.uk, 2016)

Data related to construction of activity programmes within a digital model

There are three main secondary data sources that contain data related to travel activities in the context of transport studies in a UK context. These includes 1) Census data 2) UK National Travel Survey and 3) Time use diary. A forth type Global Positioning System (GPS) trajectories is compared against time use diary as they are similar in terms of describing sequential activity or movements at different level of detail.

Census data

Census data includes commuting flows for each mode of transport associated to output areas (OA) as inflows and outflows. The data can be translated to an Origin-Destination (OD) matrix with OA as Transport Analysis Zone (TAZ) most suitable for a classical four step transport demand model. Where a disaggregated microsimulation model is required, for example to study specific difference in socioeconomic demographics, the aggregated socio-demographic data can be “allocated” to individuals through mathematical methods such as Iterative Proportional Fitting (IPFP).

UK National Travel Survey

The UK National Travel Survey is household survey conducted with a sample population in the UK aimed at “monitoring long term changes in personal travel and understanding the use of transport facilities made by different sectors of the population“. An aggregated dataset can be obtained from Department for Transport via National Statistics (Department for Transport, 2017). The aggregate dataset includes statistics such as mode of transport, car ownership; distance travelled using different mode of transport by region. A disaggregated dataset from year 2002-2017 is available on UK Data Service. (ESRC, 2012) The disaggregated dataset contains survey data for household, individual within household, trips (with a single main purpose) and stages (segments within trips).

Time use diary

Time use diary is a large-scale household survey includes time diaries of how people spend their time from a self-reported survey. It has been conducted in the year 2014-2015 (Gershuny and Sullivan, 2017) in the UK. The diaries include a set of locations and activities recorded in ten minutes intervals. The UK 2014-2015 data set contains 16533 observations, over 5000 people and 4733 households. Similar survey has been conducted in various countries including USA and Japan that are available online. An internet search indicates China has time use survey in 2008 and 2018 conducted by the China National Bureau of Statistics. (Chinadaily.com.cn, 2018)

The data granularity and data structure of time use diaries is the most suitable out of the three datasets described above in understanding activity patterns.

GPS trajectories

Another type of dataset that is useful in understanding activity patterns is GPS trajectories that are geo-located points recorded at an interval with timestamps that can be converted into a path. While Global Positioning System (GPS) trajectories has the benefit of being geolocated at a high resolution and a wide spread use of GPS integrated smartphones, privacy is a major challenge in GPS data. To date, there are no known publicly available GPS trajectories that are collected from a defined population or as sample of a population.

There are several key differences between time use diaries and GPS trajectories. Time use diaries are self-reported household survey of individuals’ time allocation, they are not geo-located, and they include named locations, types of activities not limited to travel activities and mode of transport use when travelling. GPS trajectories aims to capture real behaviour although GPS signals may be lost in certain area result in missing data and an incomplete path. They are geo-located and can be easily related to a geographical space. Named locations, types of activities and mode of transport require additional post-processing by combining additional datasets or built-in to the data collection method along with collection of GPS data.

	Resolution of travel activities	Spatial resolution	Data source and availability
Census	Flows between Output Area (commuting only)	Output Area	Office of National Statistics Datashine
UK National Travel Survey	Households Individuals (within household) trips over seven days. Travel activities only.	Available data provides Primary Sampling Unit (PSU) as broad regions in the UK e.g. North West, South East	National Statistics (gov.uk) UK Data Service
Time use diary	Households Individuals (within household) activities and named location in sequence. Survey designed to capture one weekday and one weekend day activities.	Geographical information not found in available data	UK Data Service
GPS trajectories	Individuals Travel activities may be inferred from raw trajectories with additional data analysis and processing.	Typically geographic coordinates in sequence	Usually proprietary. Not publically available for a defined population.

Table 18. Summary of comparison between different types of secondary datasets typically used in transport studies

This study employs the UK time use diary 2015 as a secondary data source as a basis for the definition of activity programmes and the types of opportunities for activity participation in the urban condition.

5.2.3 Technical requirements

Beside a digital representation of urban conditions and activity programmes, both in the form of visual representation and static representation with their attributes (Ozel, 1993), there is a need of specialised processes in order to represent the process of the system and process relevant to the topic. This will be described in the algorithmic procedure section.

5.2.4 Constructing urban conditions

5.2.4.1 Types of spatial functions as opportunities for activity participation

Activity Locations		**Time use**		**Land use (NLUD)**		**Building use (UK use class)**		**OpenStreetMap convention**
ID	**Short name**	**Code**	**Label**	**Code**	**Group level**	**Class**		**Tag building/ground**
11	Home	11	Home	U071	Dwellings	C3, C3	Dwellinghouses, Houses in multiple occupation	building=residential, house, terrace, semidetached house, detached, apartments
		12	Second home or weekend house					
13	Work	13	Working place or school		Work (note 1)	B1, B2	Business, General industrial	
10	School			U083	Education	D1	Non-residential institutions	amenity=kindergarten, college, school, university, music_school
14	Other peoples home	14	Other peoples home					
15	Eatery	15	Restaurant, cafe or pub	U093	Restaurant and cafe	A3	Restaurant and cafe	amenity=restaurant, pub, cafe, bar, food_court, fast_food
				U094	Public houses and bars	A4	Drinking establishments	
16	Sport	16	Sports facility	U044	Sports facility	D2	Assembly and leisure	building=sports centre, sports hall leisure=fitness_centre,fitness_station, golf_course, pitch, swimming_area, swimming_pool sport=*
17	Art	17	Arts or cultural centre	U043	Libraries, museums and galleries	D1, D2	Non-residential institutions, Assembly and leisure	building=museum amenity=library, arts_centre, community_centre, planetarium, theatre

	18	Park	18	Parks, countryside, seaside, beach or coast	U041	Outdoor amenity and other spaces			leisure=park
	19	Shop	19	Shopping centres, markets, other shops	U091	Shops	A1	Shops	building=retail, supermarket
	20	Hotel	20	Hotel, guesthouse, camping site	U072	Hotels	C1	Hotels	building=hotel
					U045	Holiday parks and camps			

Table 19. Mapping corresponding identifier between Time use survey 2014-2015, National Land use database, UK Town planning use class and Openstreetmap attributes

5.2.4.2 Constructing transport infrastructure

Road and street in the model are largely based on the specification of OpenStreetMap. The alteration of road and street network is not fully explored in this study but it is possible within an architectural design context. This is demonstrated in the custom tool within McNeel Rhino Grasshopper. McNeel Rhino Grasshopper is a common software that enables algorithmic procedures to be integrated within an urban design or architectural design process (Rakha and Reinhart, 2012; Feng, 2013; Abdulmawla *et al.*, 2017).

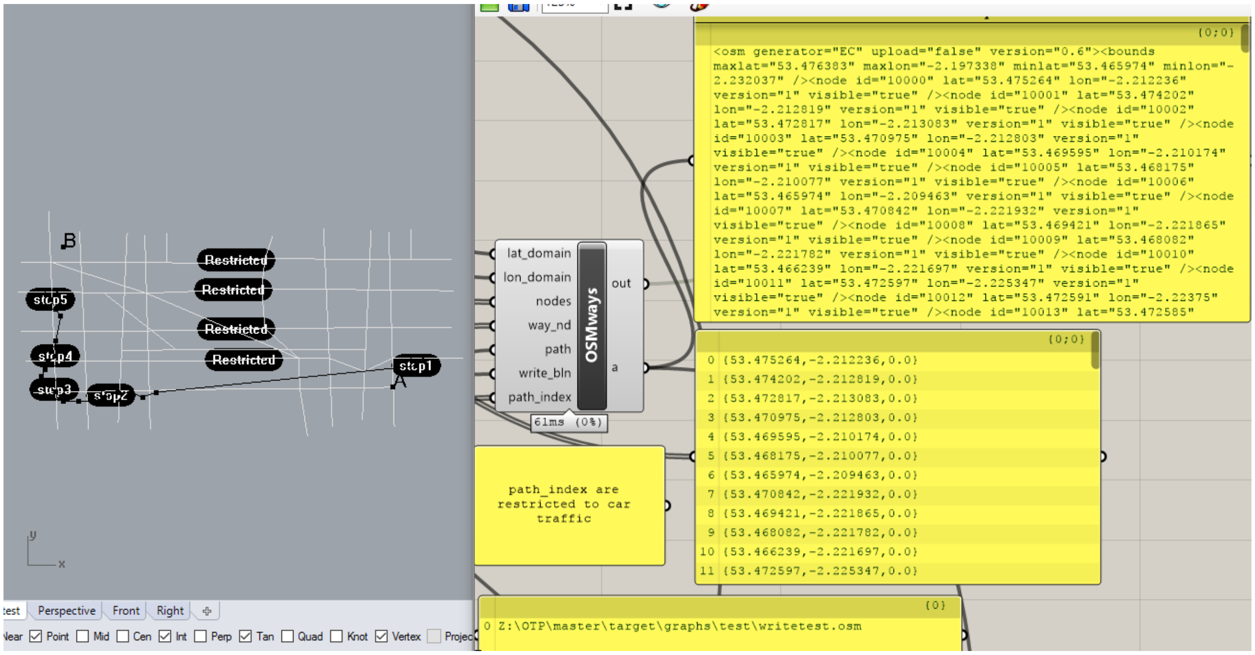

Figure 30 A basic OSM editor within a McNeel Rhino Grasshopper environment (Author's own)

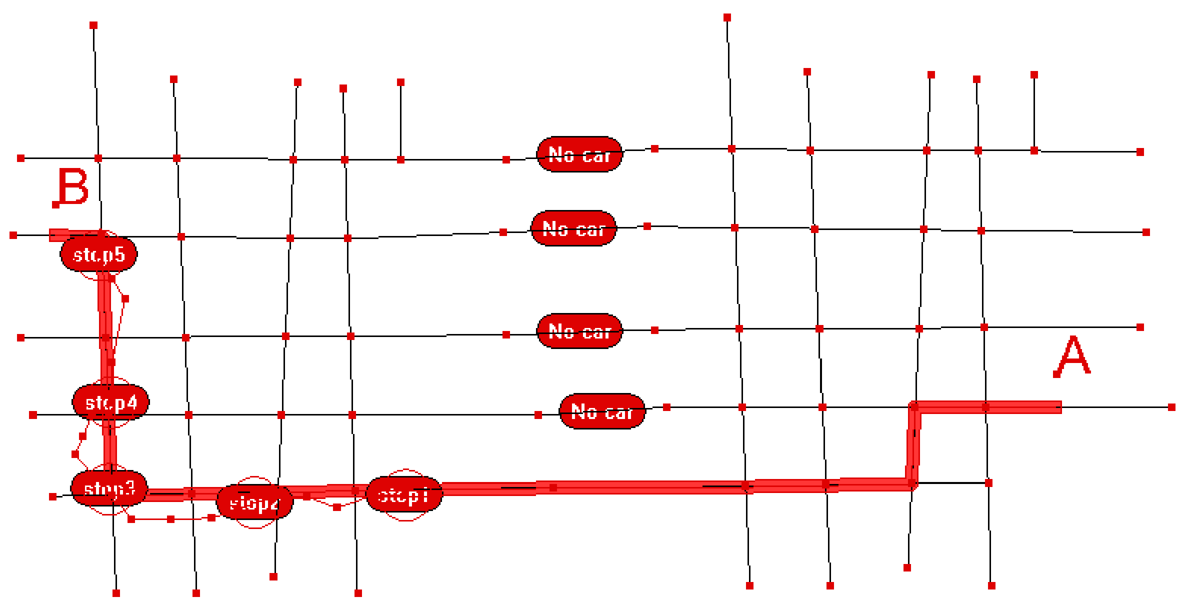

Figure 31 Restrictions to cars can be specified per road segment. This in turn affects the routing from A-B for car-based travel demonstrated in the image.

5.2.4.3 Constructing passenger service provision

Passenger service provision in the model is largely based on the specification of General Transit Feed Specification (GTFS). GTFS is a common standard for public transport schedule feed and the data is increasingly made available for different cities from local transport agencies (Transitland, 2019). GTFS enables the specification of different types of passenger transport that are timetabled.

General Transit Feed Specification GTFS specification is first developed by Google for software-based journey planning but it is now an open specification for planned public transit data. The standard GTFS is static, meaning that it contains planned scheduled data only. The GTFS-RT extension enables real time information.

Although these machine-readable formats can be represented visually, they enable routing within the transport network providing that it is modelled correctly. It is commonly used for software-based journey planning applications. In this study GTFS is used to describe scheduled passenger services that is used in OpenTripPlanner a multimodal router to provide travel times between locations. The algorithmic procedures are further described in a later section.

Two basic GTFS editor was developed in this study to aid the exploration of alternative urban conditions with passenger transport in particular. The first is a basic GTFS editor within McNeel Rhino Grasshopper and the second a basic GTFS editor with a webmap.

The fundamental GTFS requirements are included with an addition of the route geometry for each service. The basic inputs are the route of the service, stops along the route, the interval of the service, the starting time and the end time in seconds, the day in which the service runs.

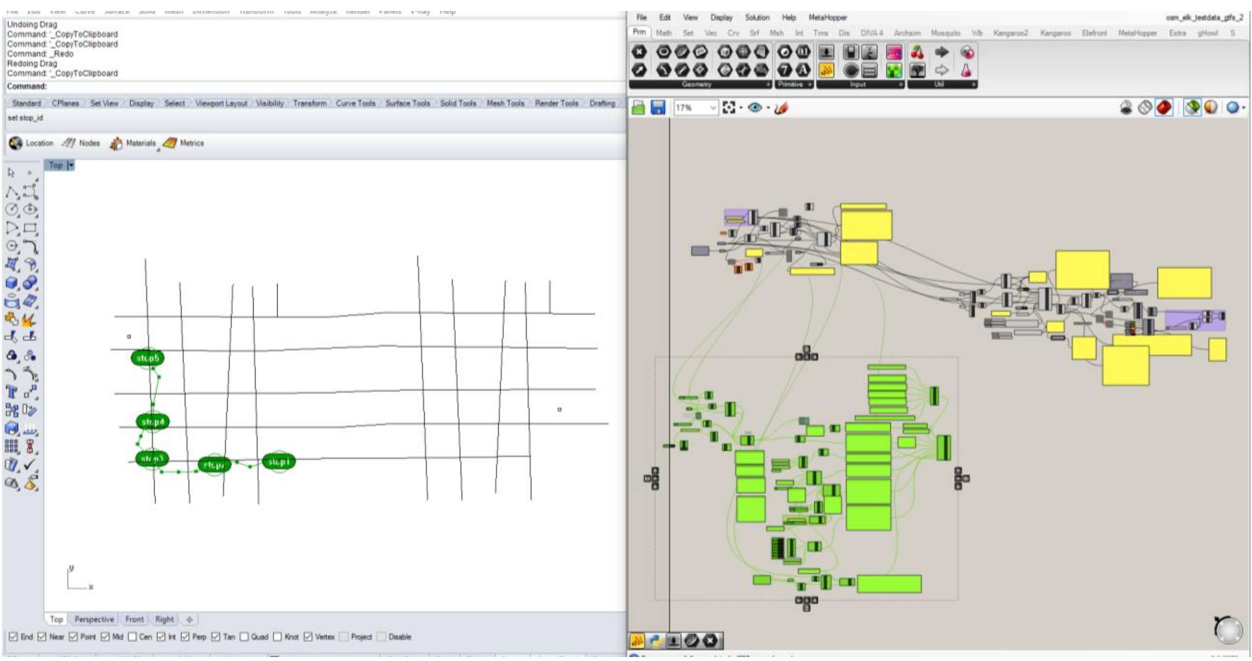

Figure 32 A simple GTFS editor within a McNeel Rhino Grasshopper environment (Author's own)

Figure 33 A simple GTFS editor with webmap (Author's own)

5.2.5 Algorithmic procedures

5.2.5.1 Introduction

As mentioned earlier in the chapter 4 research design pg144, there are two parts to the computation-enabled analytical construct developed in this study (1) an analytical framework and (2) an underlying computational model and method. This section first describes the design and implementation of the underlying model and method, the outputs that can be produced from the model and method, that lead to a description of the developed analytical framework for comparison of travel modes based on the outputs from the model and method.

The goal of the underlying model and method following the basis form PESASP is to search for possible combinations of opportunities for activity participation and transport services where an input of daily activity programmes can be performed. This is highly relevant especially in a user-centric context that is much related to the urban conditions. An example from an applied study that employs PESASP to study the public transport provisions in the city of Karlstad follows: if one has to bring a child to a nursery before work that starts at a specific time and collect the child at a specific time after work, what are the possible combinations of residential location, workplace and nursery that can satisfy the time requirements? In order to arrive at the location at the right time, certain opportunities of workplace and nursery in combination are difficult to reach by certain travel modes within the space and time constraints.

The outline of the algorithm procedure to produce a set of possible combinations of urban opportunities per travel mode for a daily activity programme based on the theoretical constructs from space time model is as follows:

1. Input of an activity programme as a sequence of the types of location-bound activities with the durations of each activity
2. Take the first activity in the sequence
3. Find the related urban opportunities in the urban condition as the current set of urban opportunities
4. Take the next activity in the sequence
5. Find the related urban opportunities in the urban condition
6. For each of the current set of urban opportunities, find whether the each of second set of urban opportunities from step 5 is reachable within the timeframe between first and second activity.
   If an urban opportunity from the second set is reachable from an urban opportunity from the first set, proceed and repeat steps 4 to 6 to build up a sequence of urban opportunities until the sequence of activity programme ends. If it is not reachable then the sequence of urban opportunities does not meet the sequence of activity programme.

While the above provides a general outline, some adaptations are required for specific questions. For example, in the example activity programme described earlier, there are certain activity locations such as home and nursery that are expected to be the same within a sequence. Additional steps are required at step 4.

Step 1-6 forms the core of the underlying model and method to search for possible combinations of urban opportunities per travel mode for a daily activity programme. Step 6 make use of a multimodal routing engine that enables the search for possible connections from one activity to the next activity within time limits with respect to the transport infrastructure or services available in an urban context.

In the context of analysis of the opportunities for travel modes to conduct daily activities, the first question is what are the differences in the number of urban opportunities that can be reached to conduct a certain sequence of location-bound activities by different travel modes. The possible combinations of urban opportunities per travel mode can be compared per location and as an overall number. The spatial extent of urban opportunities that are accessible to perform daily activity sequence can be compared between travel modes. This study visualises the set intersections of the sets of possible combinations of urban opportunities per travel mode to aid the comparison between passenger transport, drive and walk to aid assessment of the opportunities for mode change in alternative urban conditions.

The following sections describes the algorithmic procedures for (1) possible combinations of urban opportunities based on activity programme (developed in this study) (2) multi-modal routing (integrated for use within the main procedure, developed tools around it to manage specific inputs and outputs required for the analytical construct) and (3) procedures to produce visual aids for the comparison of travel modes based on the possible combinations of urban opportunities (developed in this study).

5.2.5.2 Possible combinations of urban opportunities based on activity programme

The goal of the underlying model and method is to identify the combinations of ways in which an activity programme can be performed in an urban context. Algorithmic procedure is written in python to search for matches between an activity programme and the opportunities for activity participation per travel mode. The possibility to reach from one opportunity to the next within a given timeframe is influenced by the transport network and the passenger transport schedules.

Activity programme provides a sequential timed sequence of the types of location-bound activities where travel is required to physically move from one physical location to another to participate in location-bound activities. Defined spatial functions facilitates urban opportunities for activity participation such as residential, workplace, schools and shops etc. Activity programmes includes specification of timeframes between activities. For example, work or schools usually start at a specific time and ends at the specific time. Further elaboration of how time is allocated for activities by different people and generalisations such as travel time budget and travel time ratios (Dijst and Vidakovic, 2000) is a larger topic in literature. While individual and household daily activity sequences are an integral part of space time models, this study tends towards a focus on the urban conditions. The need to include the considerations of individual space and time constraints is acknowledged through identification of activity sequences that is more than commuting to investigate the properties of space time model.

The travel possibilities between urban opportunities within timeframe per travel mode in the developed space time model is determined by the fastest route by the corresponding travel mode. Timeframe with a tolerance of 5 minutes included in the model and the start time of the location-bound activities are fixed (e.g. arrive by 9:00am) for the experimental case studies that can be specified for in future studies. Each travel mode has their own characteristics that is reflected in the multi-modal routing procedure and the data inputs for the road, street and public transport schedules. For example, speed regulations, one-way restrictions, turn restrictions are included in the road network through specified attributes in each road segments. Public transport includes stops/stations, routes, arrival, departure times specified in the GTFS standard. A multimodal router includes transfers between two services and the walking trip from any location to the stops/stations. The fastest route is used to find the maximum reachable urban opportunities next in the activity programme within the timeframe under the best possible situation. The road network in this implementation of the model does not include traffic which would affect travel time. However, there are ways to incorporate generalised traffic in the underlying router which is worth further investigations. The choice of multi-modal routing procedure is described in the next section. The limitations are further discussed in the final limitation section.

Figure 34 Simulated space time paths for an activity programme sequence H-W-Sh-H

A search for the activity programme sequence of H-W-Sh-H and the possible combinations in an urban situation given a simple testing set of different types of opportunities for activity participation (Red-H, Blue-W, Yellow-Sh) and an underlying transport network for routing. Space Time Paths visualised following time-geography conventions.

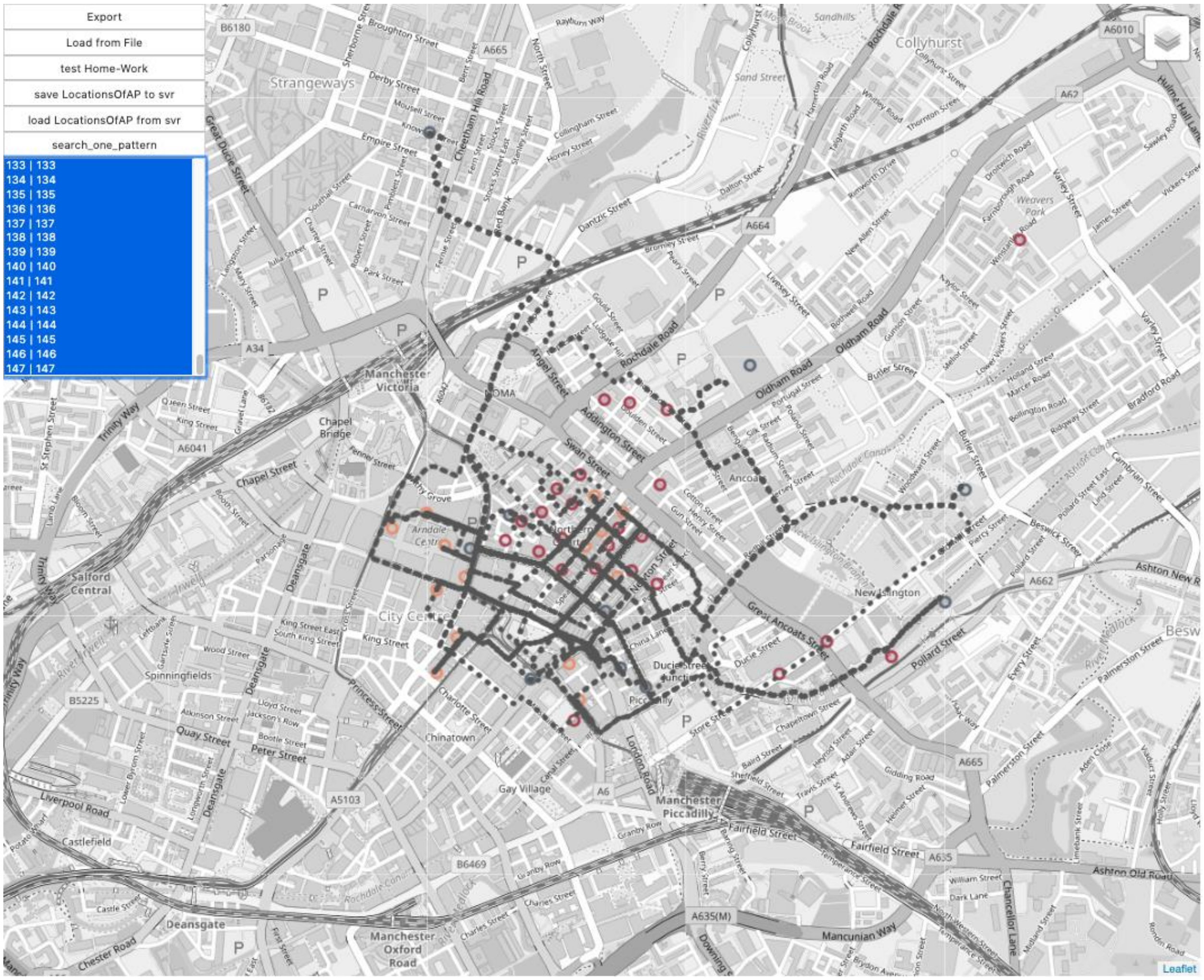

Figure 35 Simulated space time paths for an activity programme sequence H-W-Sh-H

A search for H-W-Sh-H limited to walking as the travel model using a testing set of different types of opportunities for activity participation and road and street network data from OSM for a region in Manchester.

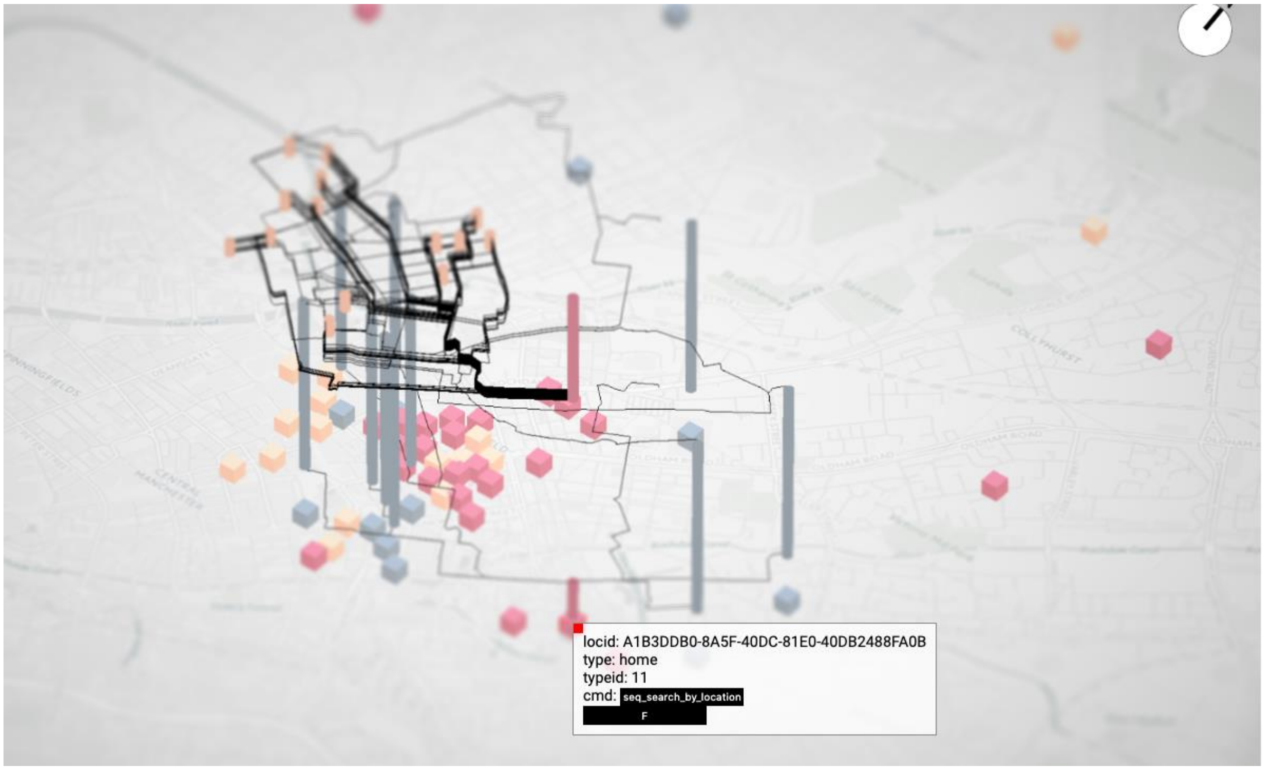

Figure 36 Simulated space time paths for an activity programme sequence H-W-Sh-H

A search for activity programme of H-W-Sh-H limited to walking as the travel model from one specific opportunity of activity participation. The possible Space Time Paths are visualised indicating the combinations of opportunities of activity participation expressed within the activity programme.

5.2.5.3 Multi-modal routing

Routing in this section refers to an algorithmic process to deduced routes from two points in geographical space computationally from a transport network that is described as a network graph. A network graph is a mathematical structure in discrete mathematics. Router is a general term that refers to a piece of software that enables the input of two points in geographical space and produces deduced routes given a transport network as a network graph. All software routers involve an algorithm for routing.

There are three ways in which routing as an algorithm process is used, relevant to transport/travel-related studies that involves geocomputational methods (1) within a router to produce routes between two points in geographical space given a transport network as a network graph (2) analysis of network graph where the routing algorithm is a procedure in combination to other steps towards results for analysis and (3) web-based journey planners in the most applied level as an instantiation for an application.

This section follows the structure where (1) the underlying principles for routing algorithm is briefly described (2) the use of routing algorithms in different fields of study relevant to the movement of people between physical space in an urban context (3) the differences between different use (4) what is available and how it is different from routing services provided by mapping companies (5) what is used in this study and its relations to the construction and alterations of a transport network and schedules in the design space.

Background

Not all routers or network analysis are the same. There are multiple ways in which routing can be conducted. A common approach in GIS-based studies for transport network analysis is though the Network Analyst extension in ArcGIS.

Although the field is constantly evolving, the common approach of router in architectural use has been the use of the Dijkstra algorithm (Dijkstra, 1959) or its variations on a basic network description of transport infrastructure. There are substantial amount of work that has been done in research into routing algorithms, such as Bast, and other alternatives not based on Dijkstra’s formulation such as RAPTOR (Delling, Pajor and Werneck, 2015).

The choice in the use of a routing engine that was originally developed to support software-based journey planners is driven by its ability for the ease of use in different areas in the world given the wide availability of the required structured geographic data for routing and moderately wide availability of machine-readable passenger transport schedules.

Existing software-based journey planner

A software-based journey planner is a software to find one or multiple routes between two locations. The technical basis of a journey planner is a routing algorithm that operates on a graph network. A graph network in general consists of edges and nodes. In this context, as a simplified example, a graph network for a vehicle-based router consists of road segments as edges with average travel time as weights and intersections as nodes. A routing algorithm that operates on this network will be able to find the fastest routes between two nodes. In a real situation, there are additional technicalities such as turn restrictions and starting or ending at locations in the middle of edges.

The origin of software-based journey planner can be traced back to the Dijkstra algorithm based on graph theory in mathematics. (Dijkstra, 1959) The Dijkstra algorithm and its variants such as the A* algorithm with speed improvements enables the search for a shortest path by topology as well as shortest path by weighted edge within a graph network – this meant that it is possible to assign travel time as weights to each edge and to be able to find the fastest path (shortest travel time). Recent advancement meant it is possible to route base on time schedules in a time-expanded (Pallottino and Scutellà, 1998) or a time-dependent (Müller-Hannemann *et al.*, 2007; Pyrga *et al.*, 2008) graph, this enables routing for time schedule based public transport. The increased geospatial data availability and common public transport standards such as the General Transit Feed Specification (GTFS) facilitate multi-model journey planner where one route can consist of multiple modes of transport. (McHugh, 2011)

From the brief description of software-based journey planner above we can identify three types of routers based on mode of transport and by common usage: A. unimodal vehicle (excluding time scheduled public transport), walking or cycling B. unimodal public transport based on time schedule (not door-to-door, typically for a specific mode of transport such as tram or rail) C. multi-modal (typically multiple types of public transport with walking connections)

From an algorithmic and data requirement point of view, a type A router for unimodal vehicle, walking or cycling routing is completely separate from a type B router for unimodal public transport. A multi-modal router is a combination of type A and type B where geospatial data for walking is required to connect multiple separated services with a different board and alight locations such as stops or stations as well as origin and destination for a door-to-door journey.

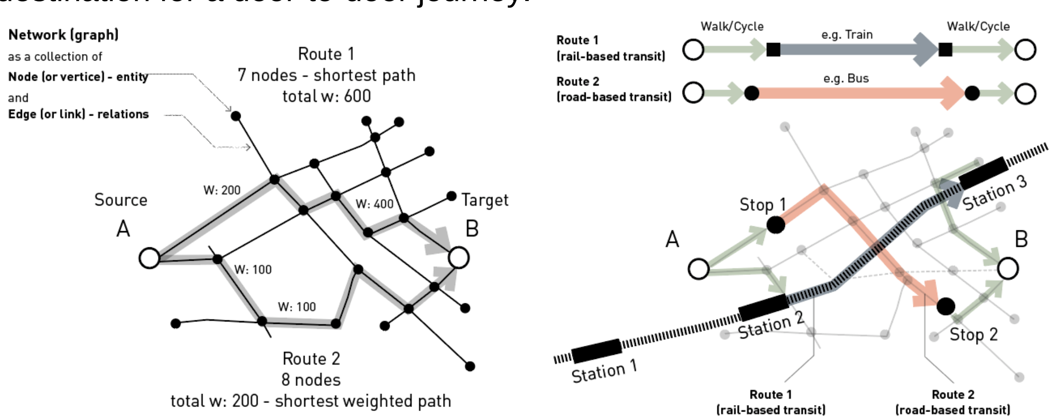

Figure 37 Differences in movement between A-B between personal modes (left) and passenger transport with stops/stations and time schedules (right). Different requirements on the software router.

There are three categories of "using" a software-based journey planner. Firstly, journey planner as an application for general users – the ones that we use in mobile phones, or as a web application (web app). Secondly, application programming interface (API) where providers provide the information of routes between two locations through a web service query. Finally, a piece of software that can be deployed as a web service and proprietary data can be incorporated for the use of journey planning. In order to produce a journey planning application, either an API or a piece of software is required.

The following table provides a non-exhaustive overview of existing software-based journey planner that is available in the UK with the identification of router capabilities by mode of transport and usage category.

		Usage				Router capabilities by mode of transport					Route Information			
		Application		API (router)	Software	A - Unimodal		B - Unimodal		C -Multi-modal	Time	Cost	Effort (calories)	Environmental
id	Name	Mobile(Android)	Webapp			vehicle	cycle	walk only	Single public transport	Public transport (+walk)				
1	MAPS.ME - Map & GPS Navigation	1	0	0	0	1	1	1	0	0	1	0	0	0
2	My TfGM	1	1	0	0	1	1	1	1	1	1	0	0	0
3	Maps - Navigation & Transit (Google)	1	1	1	0	1	1	1	1	1	1	0	0	0
4	Citymapper	1	1	0	0	0	1	1	1	1	1	0	1	1
5	Transit Directions by Moovit	1	1	0	0	0	0	0	1	1	1	0	0	0
6	Transit: Live transit App	1	0	0	0	0	0	0	1	1	1	0	0	0
7	TripGo: Transit, Maps, Directions	1	1	0	0	1	1	1	1	1	1	0	1	1
8	HERE WeGO - City Navigation	1	1	1	0	1	1	1	1	1	1	0	0	0
9	Traveline GB	1	1	0	0	0	0	0	1	1	1	0	0	0
10	London Journey Planner	1	1	1	0	0	0	0	1	1	1	1	0	0
11	Merseytravel	1	1	0	0	1	1	1	1	1	1	0	0	0
12	MyWay	1	0	0	0	1	1	1	1	1	1	0	1	1
13	MapQuest UK	0	1	1	0	1	1	1	1	1	1	0	0	0
14	Go Smarter	0	1	0	0	1	1	1	1	1	1	0	1	1
15	Tramchester	0	1	0	0	0	0	0	1	0	1	0	0	0

16	TransportAPI	0	0	1	0	1	1	1	1	1	1	0	0	0
17	Ordnance Survey	0	0	1	0	1	1	1	0	0	1	0	0	0
18	TomTom	1	1	1	0	1	0	0	0	0	1	0	0	0
19	Bing maps API (Microsoft)	0	1	1	0	1	1	1	1	1	1	0	0	0
20	ESRI map direction API	0	0	1	0	1	1	1	0	0	1	0	0	0
21	MapBox direction map API	0	0	1	0	1	1	1	0	0	1	0	0	0
22	pgrouting				1	1	1	1	0	0				
23	opentripplanner				1	1	1	1	1	1				
24	graphhopper				1	1	1	1	0	0				
25	OSRM				1	1	1	1	0	0				
26	Valhalla				1	1	1	1	1	1				

Table 20. Existing software-based journey planner (author's own collection)

Regarding the use of a journey planner application, the minimum inputs from the user include origin and destination evident in all software-based journey planner. The minimum input includes the time of travel (with options for arrive by or depart at) for journey planner with a public transport router.

The output of a journey planner application is display in two ways. One that separates the modes by the type of router – vehicle (excludes public transport), public transport (public transit), walking and cycling. For example, Google map and directions. Another displays the outputs for multiple modes of transport. For example, Go Smarter.

There are limitations in using existing web services accessed through API.

One major issue is that it is impossible to incorporate custom geographical data such as passenger service timetable or changes in the road or street network as a user of API. Reconfiguration in passenger services or road and street network can be part of an alternative urban condition – essential in transport-integrated city design. To illustrate this as a simple example, if a road is known to close for road works over a period of time, as a user of the API, such information cannot be inserted into the query that would alter the outputs of the routing algorithm. While it is possible to build in specific functionalities to handle specific use cases, there are no inputs for custom data that allows us to answer questions such as 'what is the difference between public transport and road transport if we insert a new tram line?'

Difficult to incorporate data in the post-routing stage. For example, in the UK, all stops has a unique code but the data output of stops are typically names of the stops only. It is a challenge to map the names of the stops to a related data set where the names can have different spellings or format. For example, "Besses O'th'barn" and "Besses O th barn".

In this study, an existing software routing engine OpenTripPlanner OTP (McHugh, 2011) was used as a response to the limitations in existing web services accessed through API services. OTP has been increasing used by researchers in the transport-related studies (Yu, Shao and Wu, 2016; Pereira, 2019) but has yet to be developed for space time approach to transport studies (Charleux, 2015). The algorithm in space time models is known to be combinatorial in addition to the multiple trips within an activity sequence, it requires a large number of trip queries. OTP is able to return outputs to trip queries in reasonable time.[1]

There are still limitations such as accuracy (Wessel and Farber, 2019) and the inherent limitations of pre-planned public transport schedules not being able to reflect qualitative questions of reliability common to all network-based analysis and journey planners. Part of the limitations is beyond OTP; the router can only be as good as the data input.

[1] Note: a custom routing engine was developed before making use of an existing software routing engine. It is particularly challenging to work with public transport schedules and multimodal connections for routing especially when the computation time needs to be minimal. The algorithmic approaches underlying time-based routing has been the focus of a different field of study (for more information see Pyrga *et al.*, 2008)

5.2.5.4 Procedures to produce visual aids for the comparison of travel modes

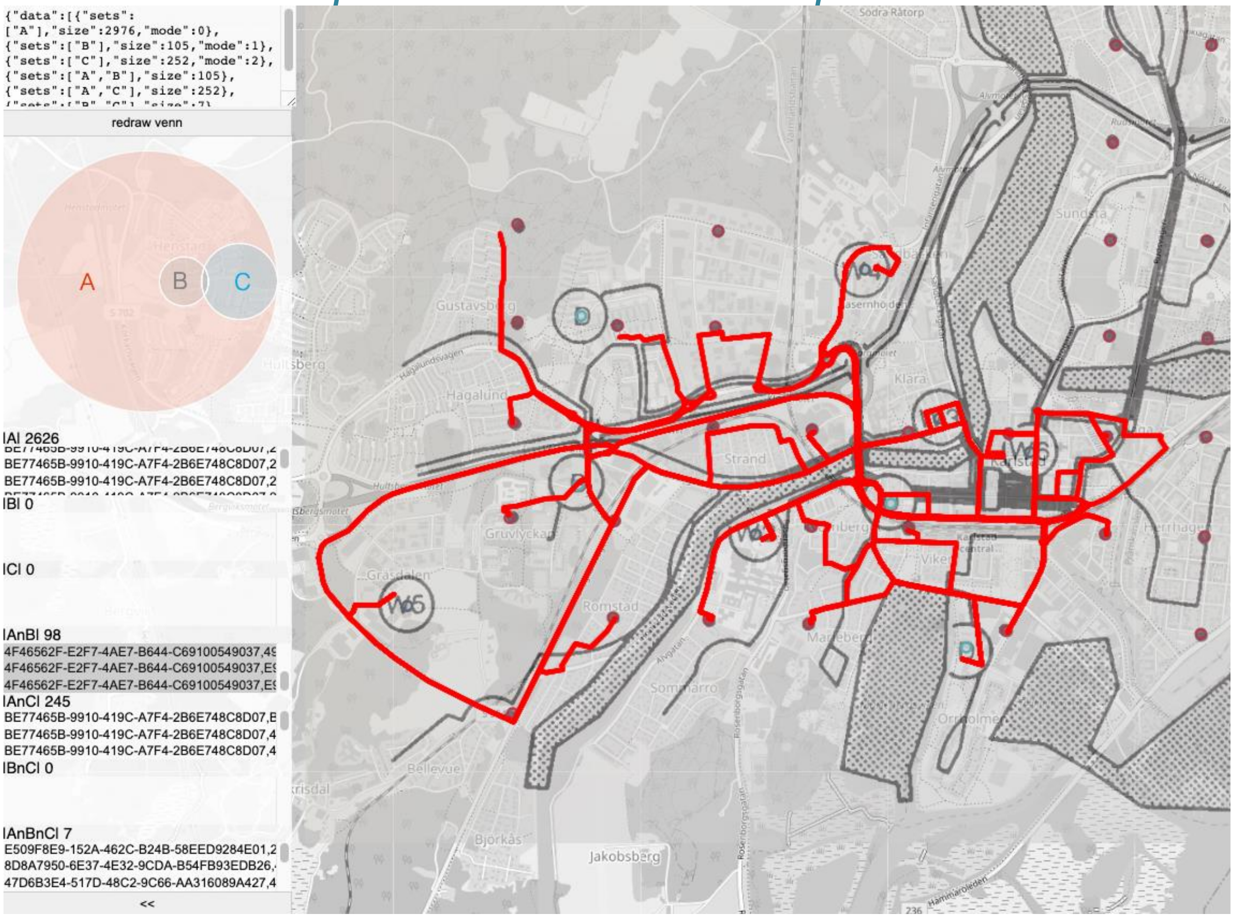

Figure 38 Set intersection between three sets of possible combinations of urban opportunities per travel mode (A: car, B: walk, C: public transport (include walking to and from station/stop)) Author's own, the outputs from a reconstruction of Lenntorp's (1978) Karlstad study in the background (image overlay over map).

Sequence of urban opportunities can be supported by all travel modes, set intersection helps to identify the set of urban opportunities that is possible only by car-based travel |A|, only on foot |B|, only by public transport |C|, by both car and on foot |AnB|, by both car and public transport |AnC|, by both public transport and solely on foot |BnC|, and by all three travel modes |AnBnC|.

One of the principles in a transport context mentioned by Nicola Kane from Transport for Greater Manchester (TfGM) [2] is to promote active travel such as walking and cycling and for public transport to compete with car use but not with active travel modes.

If public transport were to be provided in order to provide the condition for a reduce car use, the following provides an example of a possible interpretation where a maximum

[2] Presentation at the Future Mobility Symposium 2020 held at Manchester Metropolitan University on 14th January 2020. Nicola Kane is the Head of Strategic Planning and Research at TfGM

|AnC| for public transport to compete with car use and a minimum |BnC| for public transport not to compete with walking is preferred.

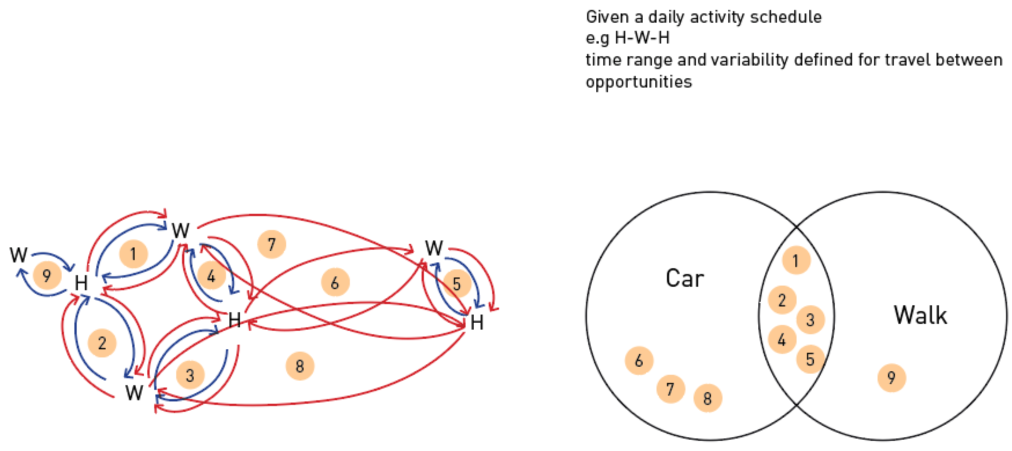

Figure 39 Identify car-based pattern and walk-based pattern

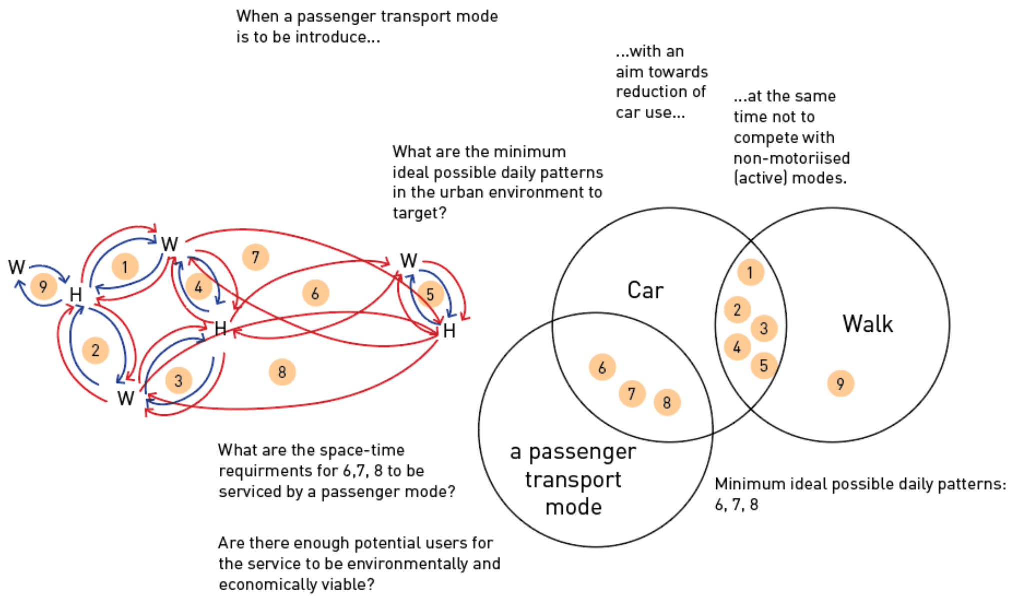

Figure 40 For a passenger transport mode to compete with car-based pattern but to avoid competition with active modes (walk-based patterns)

5.2.5.5 Technical details of implementation

Server-side procedures

Custom scripts are written in python and php. They are locally hosted on a server to perform the main algorithmic procedures that matches activity programme as an input to the urban condition and proceed to search and outputs the possible combinations. The locations of opportunity for activity participation is stored initially on a local postgresql with postGIS, a set of text files is used instead at a later stage for the ease of explorations.

OpenTripPlanner (OTP) version 1.3.0 is used in this study. The transport network graph has been built against this version. A custom socket server and client written in python is used to initiate rebuild process on OTP when there are modifications to the transport network.

Visual procedures

There is a mixture of interfaces that can read the outputs from the custom scripts both in a web-based context and within common architectural software. Some of the functions such as the set intersection procedures on the outputs from the server-side is conducted on the client-side with functions written in javascript.

Leafletjs is used for the web-based mapping. OpenStreetMap is used for the background raster tiles within Leafletjs. D3.js is used in the custom timeline diagram to visualise activity programme. venn.js (https://github.com/benfred/venn.js/) is used for the venn diagram. Three.js is used for its webgl environment as a basis for the 3D space-time path visualisations.

McNeel Rhino Grasshopper 5 with ghPython is used for custom scripts required for the custom GTFS outputs and modification of OSM data. The grasshopper plugin Meerkat was used to convert between latitude and longitude web projection (4326) and OS coordinates (27700) for use within Rhino environment.

Others

Cumulative opportunity measure and other accessibility measures has been reconstructed within McNeel Rhino Grasshopper environment based on diagrams and description by Guy (1983).

5.3 Case study experiments

Two case study experiment is designed to examine the properties of the developed analytical construct. As mentioned earlier in section 5.2.1 pg156, the underlying model of the analytical construct consists of four main variables each with its specific set of data requirements and are interrelated through the space time model. The four main variables include (1) the opportunities for activity participation (OAP) by types with geo-positions (2) the physical transport infrastructure including road, street for road vehicles, cycling and walking (3) passenger transport routes and schedules (4) activity sequence. While all four variables can be reconfigured, the case study experiment focuses on the reconfiguration of OAP and the introduction of new passenger transport most relevant to the identified problem of passenger transport in the wider context.

5.3.1 Baseline condition

In order to conduct the experiments to examine the properties of the analytical construct, a baseline urban condition is developed using the Manchester as the context. The road and street network data are sourced from OpenStreetMap and the public transport GTFS schedules from 2017 was used as a basis for the existing passenger transport modes. A set of sample points of residential and workplace are used as approximation of the urban opportunities. Existing primary school locations is used as sample points for schools. The activity programme used for testing follows the sequence used by Lenntorp's (1978) in Karlstad. The activity programme involves bringing a child to a primary school, get to workplace by 9:00am, pick up child from the same primary school after work.

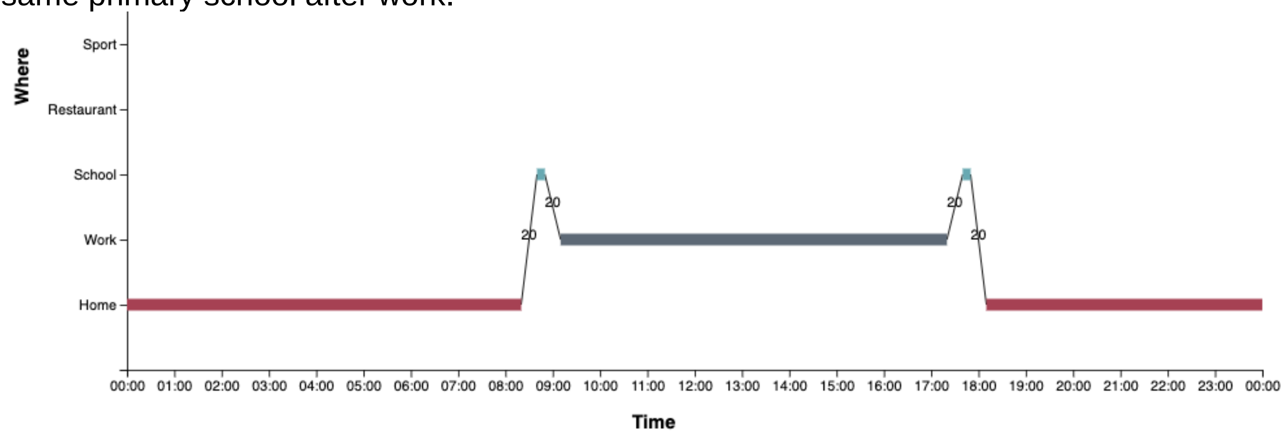

Figure 41 Illustrated timeline of the activity programme used for testing with the types of location-bound activity on the y-axis and time on the x-axis

It is worth reiterating one of the main differences between the consideration of a complex trip-chain like the example above and a trip-based approach. On the trip-by-trip basis, simply from home to work it may seem that it is open to all kinds of possibilities. With the considerations of the whole sequence of an individual's space and time constraints, the possibilities are limited.

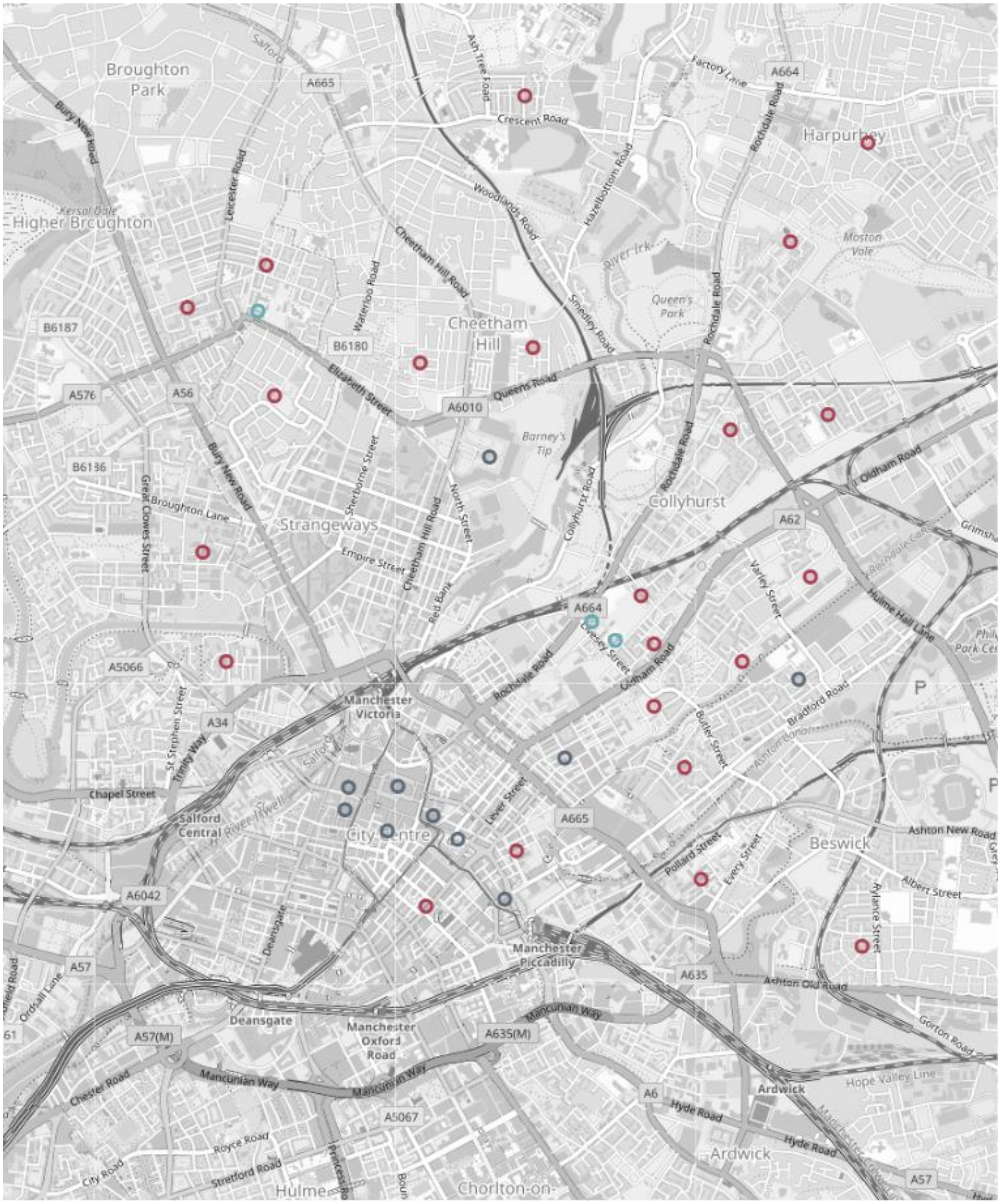

Figure 42 The setup of urban opportunities used as a baseline urban condition (Red-Residential, Blue-Workplace, Aqua-Primary school)

The underlying space time model developed in the study is used to produce the possible combination of urban opportunities based on the activity programme for three types of travel modes: A – Car, B – Walk and C – Walk & Public transport.

In this baseline condition, there are 594 possible car-based combinations, 298 possible walk-based combinations and 63 possible public transport-based combinations.

Figure 43 Car-based combinations and extent

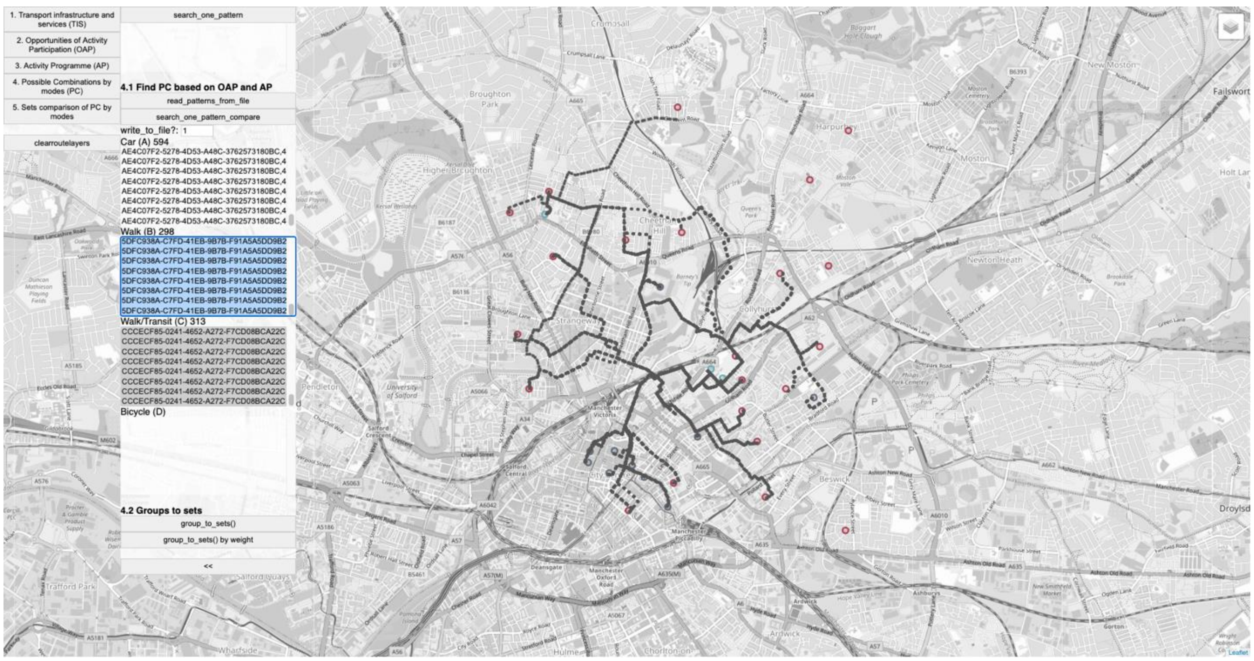

Figure 44 Walk-based combinations and extent. Note that the activity programme cannot be performed from some of the residential locations

Figure 45 Public transport-based combinations and spatial extent where the public transport can be used to perform the activity programme. Note that the majority of households on to the West and East are not served by the public transport services.

The procedures for comparison are used to aid analysis of the sets of combinations by different travel modes.

Figure 46 Venn diagram indicate the sets intersection between A:Car B:Walk and C:Public transport. Combinations of urban opportunities that are possible by all travel modes |AnBnC| are highlighted on the map.

In this baseline condition, 304 combinations that can only be possible with a car |A| , 24 combinations that can only be possible on foot |B|, 3 combinations that are only possible with public transport |C|, 235 combinations that can be conducted by either car or on foot |AnB|, 21 combinations that can be conducted by either car or public transport |AnC|, 5 combinations that can be conducted by either public transport or walking |BnC|

and finally 34 combinations that can be conducted by any of the three types of travel mode |AnBnC|.

5.3.2 Case study experiment 1: New passenger service

The first case study experiment is designed to explore the reconfiguration of passenger services. A new hypothetical bus service is inserted into the model and compared against the baseline analysis.

The study is conducted under the same setting as the baseline condition with the exception of the introduction of a new hypothetical bus service following a certain route with specified time and stops on top of the existing public transport network. From the previous setup of baseline and the analytical outputs, it is observed that the connection between East to West for public transport is limited while there is a school in the North West and there is limited access to schools from the residences in the East. The new hypothetical bus service with the route place along this East to West connection is introduced to the model as an attempt to connect these.

The question is whether the new service increase the possibilities for the use of public transport of the households in the North West and in the East given the individual space time constraints set out in the activity programme?

Figure 47 Introduction of a hypothetical prospective passenger service e.g. a bus service into the model. In particular, to connect the disconnected school to the north west to residential locations in the east. (underlying map for reference from OpenStreetMap)

5.3.2.1 Analysis

Figure 48 baseline condition

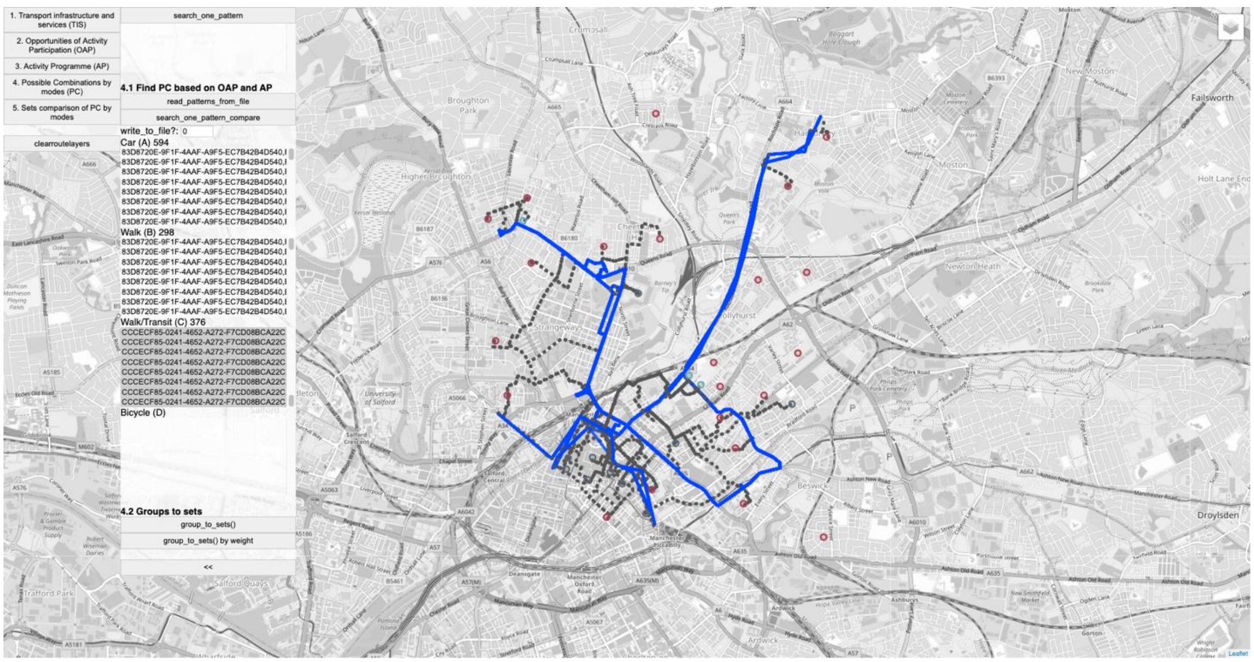

Figure 49 alternative urban condition with a new bus route and service

Figure above with the baseline condition and below with the prospective passenger service e.g. bus route. The service increased the number of combinations of urban opportunities and the connection between the school in the North West and the residential locations in the East as expected. There are also additional possible public transport connections to conduct the activity programme between the residential locations in the North west to the schools in the East.

	Baseline	+ new bus service
Car-based	594	594
Walk-based	298	298
Public transport-based	63	376

Table 21. numerical results comparison between baseline and new bus service

5.3.2.2 Interpretation of results

By identifying the service gaps from the space time model, it is possible to plan for public transport that fills the gap for a particular sequence of daily activity that considers both spatial connections between opportunities and the potential temporal needs. The prospective passenger service introduced here is for the purpose of demonstrating and testing the analytical construct. The computational enabled construct had been developed to allow inputs from others such as transport service planners. The results enable the delineated area to locate further information. For example, it can be used to identify the household that can benefit from the new bus route and find out whether the connections are needed through further studies.

As identified in the background section, introduction of additional passenger service serves the need to increase accessibility beneficial towards the economic and social dimension but introduce additional environmental impact of the overall transport system. The ability for public transport to reduce overall environmental impact relies on its ability to reduce car use. In that sense, the analysis between the set intersection |AnC| – the combinations of opportunities that are accessible by public transport or car aids an understanding of the possibility for the use of public transport as an alternative to car in order to conduct a sequence of daily activity.

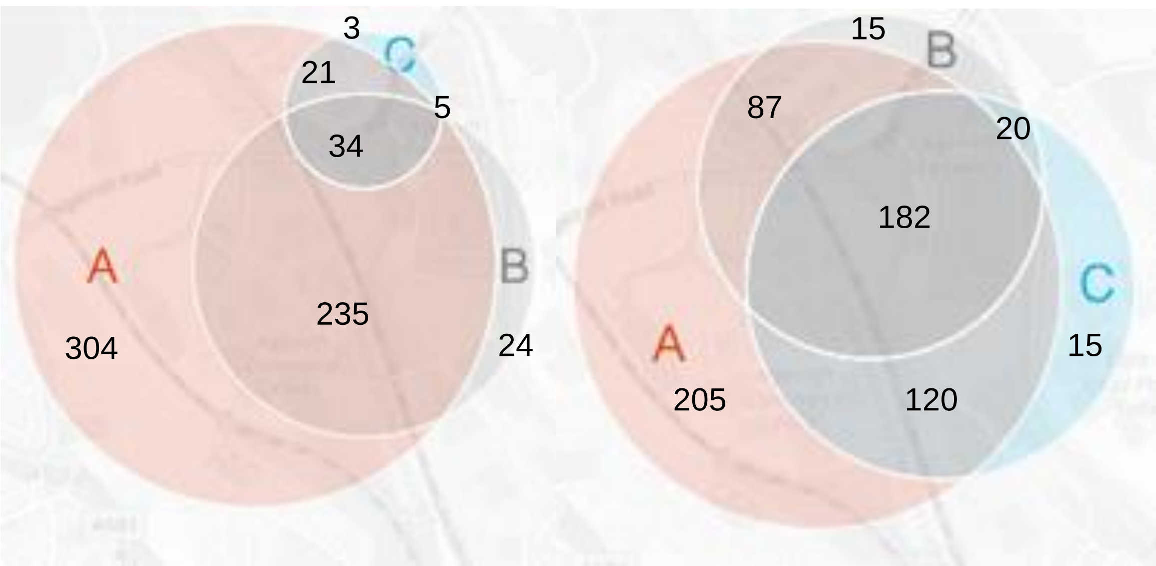

Figure 50 Outputs from baseline condition on the left and the alternative condition on the right

	Baseline	+ new bus service
|A| car only	304	205
|B| walk only	24	9
|C| public transport only	3	15
|AnB| car / walk	235	87
|AnC| car / public transport	21	120
|BnC| walk / public transport	5	20
|AnBnC| car / walk / public transport	34	182
Total	626	638

Table 22. numerical results comparison between baseline and new bus service by set intersection

In answering the question of whether the new service increase the possibilities for the use of public transport of the households in the North West and in the East given the individual space time constraints set out in the activity programme, it is important reiterate is that the activity programme not only contains the connection between residences and schools but also workplaces. The analytical construct enables the analysis of the combinations specified within the activity programme. This meant that not only does the bus route needs to connect between residences and schools, it also need to connect schools to workplaces.

As we can see the new prospective bus service has significantly increase the overlap between AnC where the set AnC (car or public transport) increased from 21 to 120. However, it is worth noting that the set BnC (walk or public transport) also increased from 5 to 20. The new bus service also increased the number of households with the possibilities to use all three types of travel modes to conduct the activity programme.

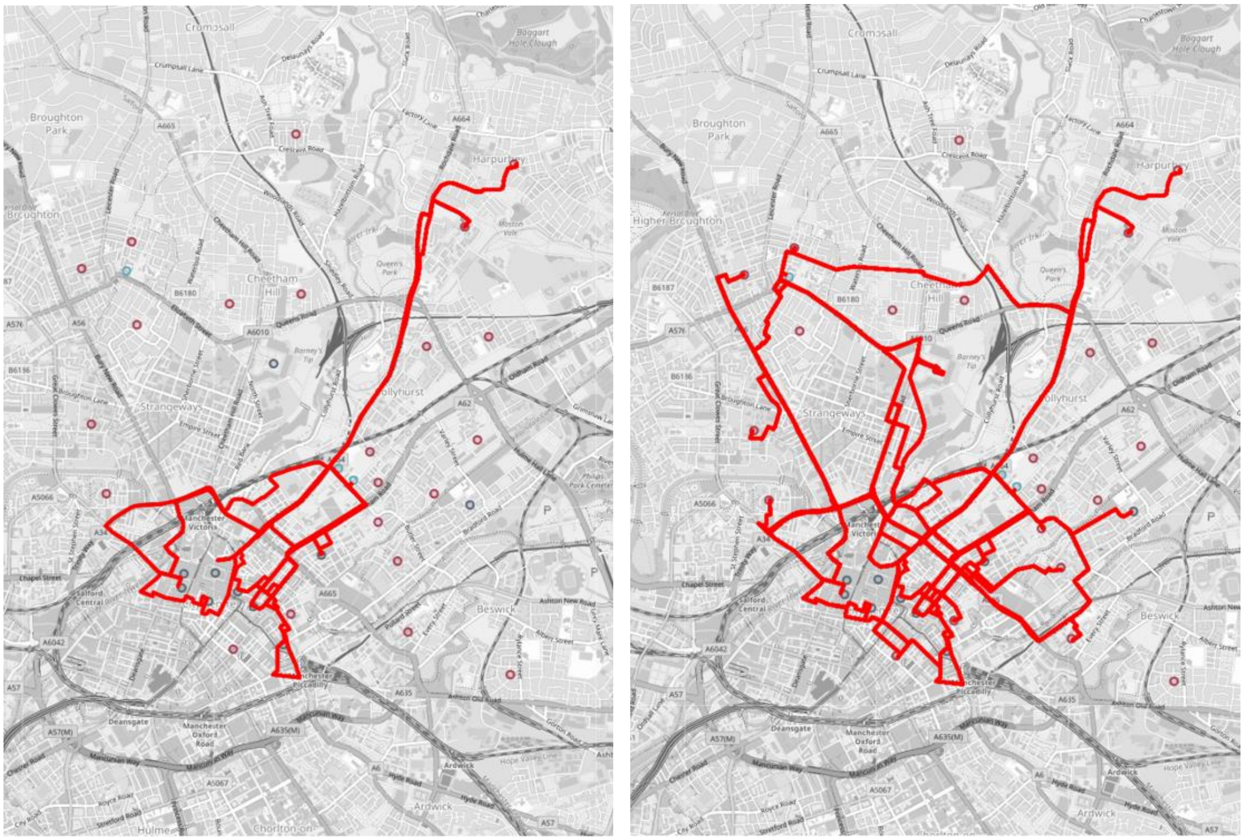

Figure 51 the spatial extent from baseline condition (left) and the prospective passenger service (right)

The set AnC (car or public transport) increased from 21 to 120. The map shows the difference in spatial extent the additional household served by both car and new bus service in conducting the activity programme. The faster routes for cars is shown in the image but what is important are the points where the routes connects.

5.3.3 Case study experiment 2: reconfigure OAP

The second case study experiment is designed to examine the reconfiguration of OAP. The study is conducted under the same setting as the baseline condition with the exception of the introduction of a hypothetical new school in a certain location. The question is whether there are higher possibilities for the use of public transport to the new school given the individual space time constraints set out in the activity programme?

Figure 52 Introduction of a hypothetical new school in the model (blue dot) as an example for testing of analytical construct

5.3.3.1 Analysis

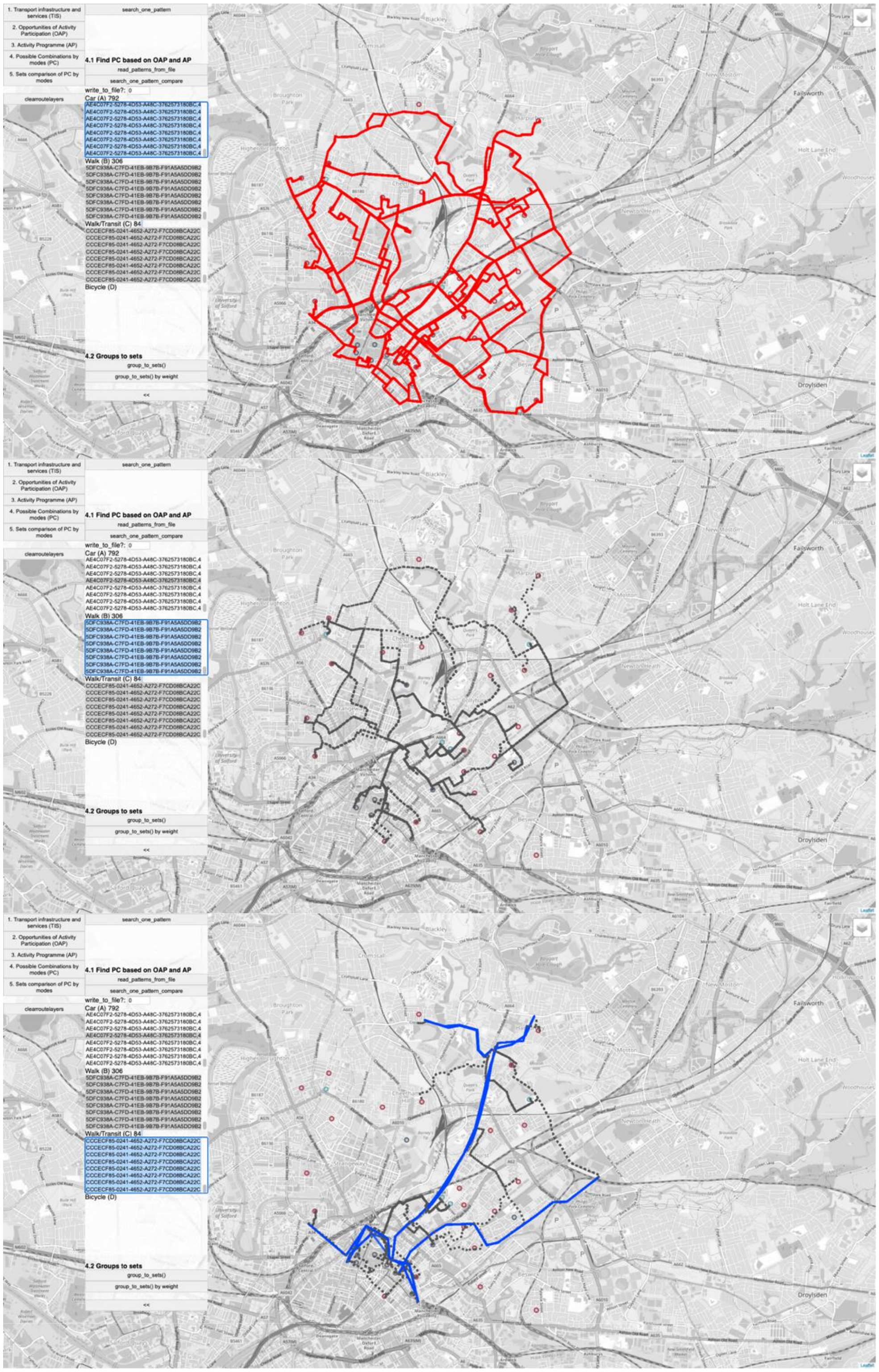

Figure 53 Top: car, middle: walk, bottom: public transport-based combinations showing the spatial extent of household facilitated by each travel mode to conduct the activity programme

	Baseline	+ school
Car-based	594	792
Walk-based	298	306
Public transport-based	63	84

Table 23. numerical results comparison between baseline and new school

Figure 54 baseline condition on the left and the alternative condition on the right

Outputs of the spatial extent and household served with both possibilities of using car and public transport based on the activity programme. The difference in the additional household served by a combination of existing public transport service, the new school is observed to the North west and in the East. Blue dot indicates the location of the new school.

5.3.3.2 Interpretations of results

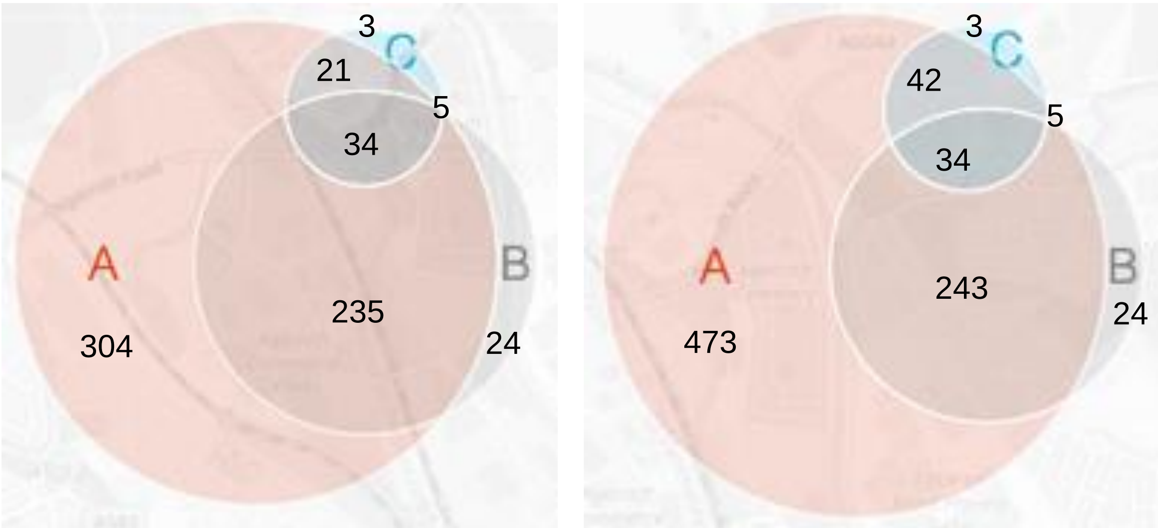

Figure 55 Outputs from baseline condition on the left and the alternative condition on the right

	Baseline	+ school
|A| car only	304	473
|B| walk only	24	24
|C| public transport only	3	3
|AnB| car / walk	235	243
|AnC| car / public transport	21	42
|BnC| walk / public transport	5	5
|AnBnC| car / walk / public transport	34	34
Total	626	824

Table 24. numerical results comparison between baseline and new bus service by set intersection

The additional of the new school does not result in much visible changes in the venn diagram. However, the total number of combinations has increased from 626 to 824. In answering the question of whether there are higher possibilities for the use of public transport to the new school given the individual space time constraints set out in the activity programme, the new school increased the total public transport-based combinations from 63 to 84 and the possibilities to conduct the activity programme by either car or public transport |AnC| has increased from 21 to 42. It is also useful to see if there are increase in overlap between walking and public transport, where a mode change from walking to public transport does not contribute to environmental sustainability in a system level, the results indicate that there are no changes.

While the study has a focus on passenger transport, active transport such as walking can also be part of the consideration. The possibilities to conduct the activity programme by either car or on foot |AnB| only marginally increased. This indicate that not only the location of the school and the location of the residences but also the locations workplaces can influence the possibilities for walking, for the activity programme includes the combination of all three types of location-bound activities. In this instance, the workplace concentrated in the city centre are not reachable within the given timeframe by walking while bringing a child to and from on the way to work and back.

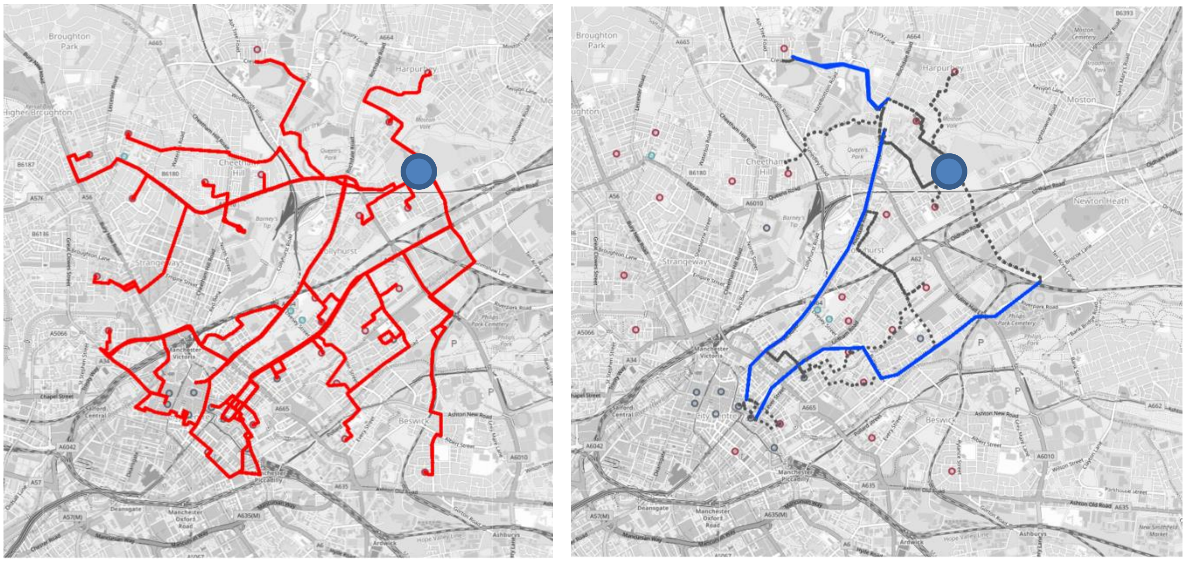

Figure 56. Combinations of urban opportunities. Left: car-based Right: public transport-based

It is also possible to conduct a search from any OAP in the model. In this example, a search from the new school (indicated by the blue dot) identifies the combinations of opportunities supported by different travel modes.

5.4 Evaluation of the computation-enabled analytical construct developed

5.4.1 Comparison to other models

While it is beneficial to evaluate the computation enabled analytical framework in terms of its fit of purpose to assess the usefulness of the construct in a city design process, the validity of the analytical framework relies on the validity of the underlying computational model and method. This section provides evidence for the validity of the underlying model and method.

Two types of comparison are conducted. The first is to compare with similar instrument in order to provide evidence for **construct convergent validity**. The second compares the new construct with common location-based accessibility measure to provide evidence for **construct discriminant validity** where differences between the measures are expected.

5.4.2 Comparison with similar construct (construct convergent validity)

The closest construct to the developed construct is Lenntorp's PESASP from which the developed construct was based on and extended through contemporary technologies and new data sources.

A study is developed to compare the new construct with Lenntorp's application of PESASP in Karlstad (Lenntorp, 1978). PESASP and the original data on the transport network used in the study is not publicly available. The urban condition is reconstructed and analysed in the closest possible approximation of the original study based on the diagrams and description from literature (Thrift, 1977; Lenntorp, 1978; Kwan, 2004a; Sanders, 2007).

PESASP enables the computation of the number of possible urban opportunities given a daily activity programme and the urban conditions. Through PESASP, Lenntorp "introduced a method facilitating enquiry into the current and future efficiency of the public transport system from the angle of the user-consumer" (Lenntorp, 1978). The study in Karlstad is formulated around the possibilities to conduct a daily activity programme in the city using different type of travel modes including walking, private car and public transport. The aim of the study is to understand the possibilities of using public transport in the City of Karlstad.

The daily activity programme that is tested includes a sequence of daily activities. Leaves home 40 minutes before work begins. Within these 40 minutes time to bring a child to a day nursery. The child is collected from the same day nursery on the way home after work. The urban condition is setup as three sets of activity locations including day nurseries, workplaces and residential dwellings. Day nurseries and workplaces are setup as specific locations, sixty-two residential locations are sampled in a grid format at a 0.5km interval. While not explicitly mentioned in the study, transport network is modelled digitally as a matrix between locations (Kwan, 2004a).

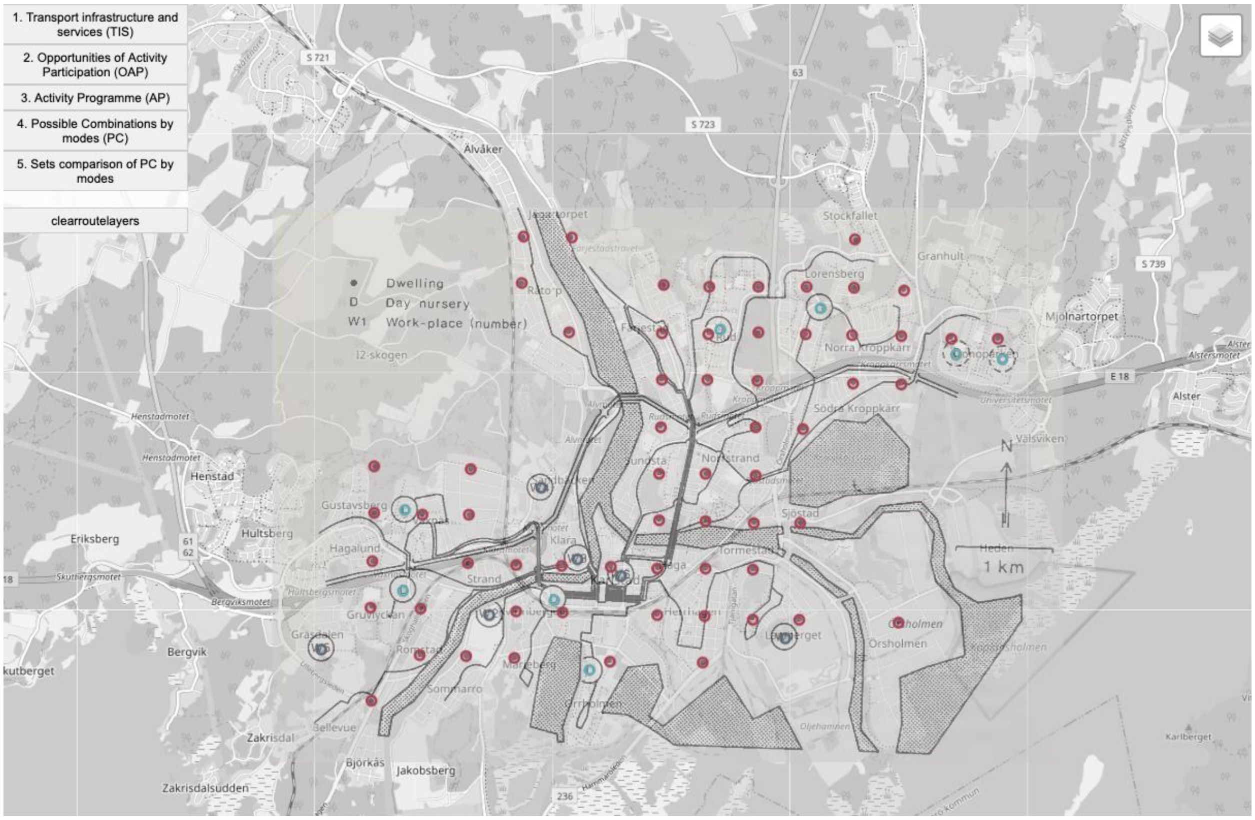

Figure 57 setup of urban oppoprtunities (red-dwelling, aqua-day nursery, dark blue-workplace) based on diagram from Lenntorp (1978) (image overay)

Results and comparisons

Figure 58 output results from developed analytical construct

Number of possible combinations of urban opportunities including day nursery and workplace from each residential location reachable at certain times of the day is recorded to be compared with corresponding outputs from the diagram in Lenntorp's (1978)Karlstad study .

Findings for construct convergent validity

In order to provide evidence of construct convergent validity, the outputs from the analytical construct developed in this study is tested for correlations with the corresponding outputs from the diagram in Lenntorp's (1978) Karlstad study.

			0	3						3			
			1			2	4	3	4	4	3		
				3		3	3	2	2	2	4	5	3
						7	5	6		5	4		
						6		5	3				
1		4				6	6	6					
1	1	4				16	7	3	1				
1		3	10	12	14	8	5	2					
7	1		5	8		4	4	2	0		0		
	1	2	4		0		2						
6													

			0	0						0			
			0			2	2	2	1	1	0		
				0		2	2	2	2	1	1	1	0
						2	2	2		2	2		
						4		2	2				
5		3				4	4	4					
5	5	5				4	2	2	1				
5		5	4	4	4	4	3	2					
5	5		4	4		4	3	2	2		0		
	4	4	4		4		3						
1													

Table 25. Left – outputs produced from analytical construct developed in this study. Right – outputs from diagram in Lenntorp (1978). Pearson correlation of the two set of results is +0.257

Limitations of the construct convergent comparison and discussions

Although attempts were made to reproduce the results, differences between the new analytical construct and PESASP is expected. There are a number of differences in the computation of travel times. While the underlying space time model and method is based on PESASP, the transport network in the space time model developed in this study is enhanced to work with current widely available geographical data for the street and road network and public transport schedules widely published by local transport agencies in a GTFS format. Beside known differences in the underlying space time model, there are some limitations to the comparison. There are no digital historical public transport schedules available for the input in the new analytical construct and the current available GTFS data on public transport for Karlstad is used in the reconstruction. The GTFS data of Karlstad was sourced from Karlstad opendata via Transitland data feed registry (Transitland, 2019). Similarly, the current road and street network are used in the testing of the new construct obtain from OpenStreetMap (Coast, 2004).

The limitations in the setup contributed to the lower than 0.5 correlation but a positive correlation is observed. Nonetheless, the comparison demonstrates (1) the ability for the developed analytical construct to reproduce analytical findings similar to constructs that are expected to be similar and (2) the ability to apply the analytical construct in different areas. Further research can be conducted with comparison to other similar models such as Dijst's MASTIC.

5.4.3 Comparison with different constructs (construct discriminant validity)

In order to demonstrate construct discriminant validity, a comparison between a typical accessibility measure, cumulative opportunity measure and the measure from the space time construct based on number of combinations of opportunities accessible per residential location. The algorithm for cumulative opportunity measure for geographic representation has been reconstructed in Rhino Grasshopper and python in this study. The formulation of cumulative opportunity measure is based on Guy's description and diagrams a study comparing cumulative opportunity measure and other types of accessibility measure in Reading, UK (Guy, 1983). See section 2.2.4 for a literature review for a description of cumulative opportunity and other accessibility measures pg83-88.

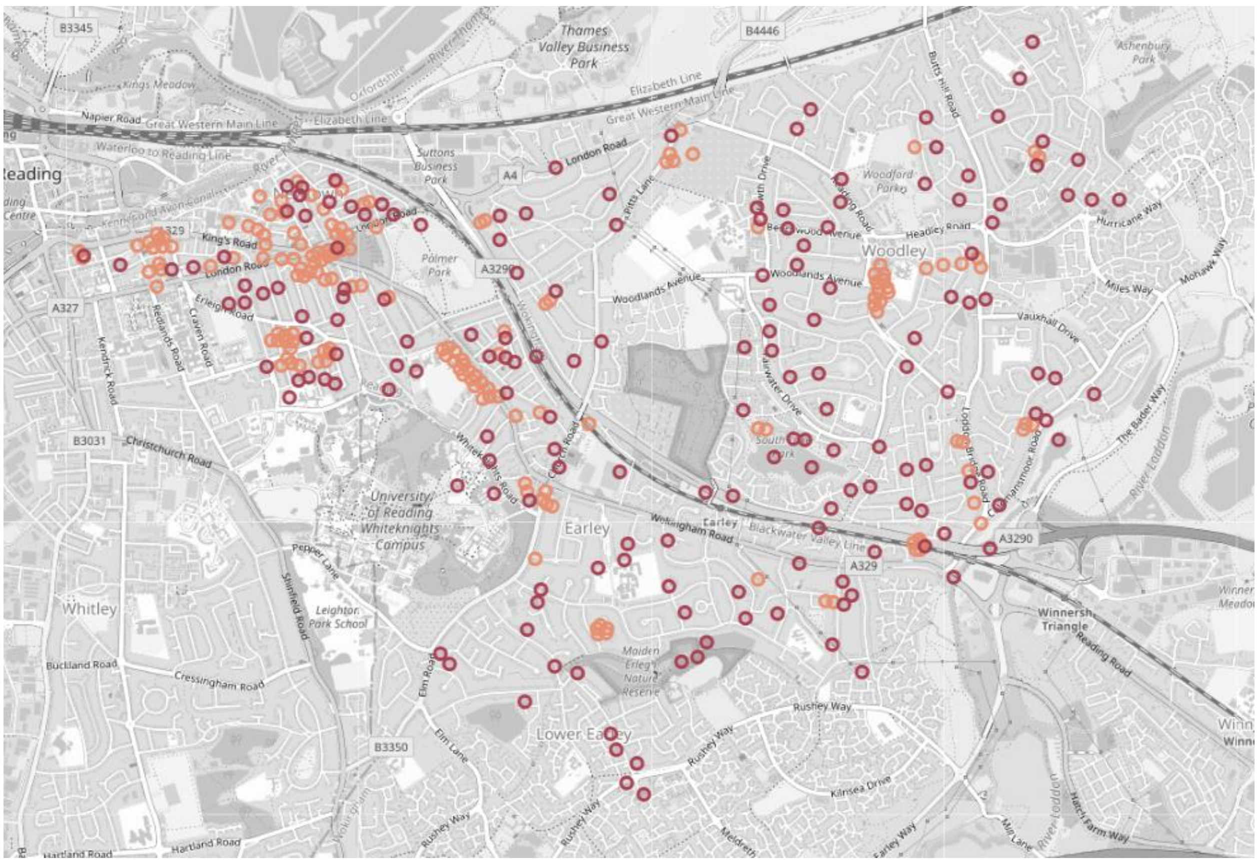

Figure 59 geolocated positions of 173 residential locations and 163 shops in Reading from Guy's experiment, redrawn and mapped based on the diagrams in article (Guy, 1983)

Results and comparisons

The simple comparison in Guy's article was setup with residential locations (in blue) and shops locations (in yellow).

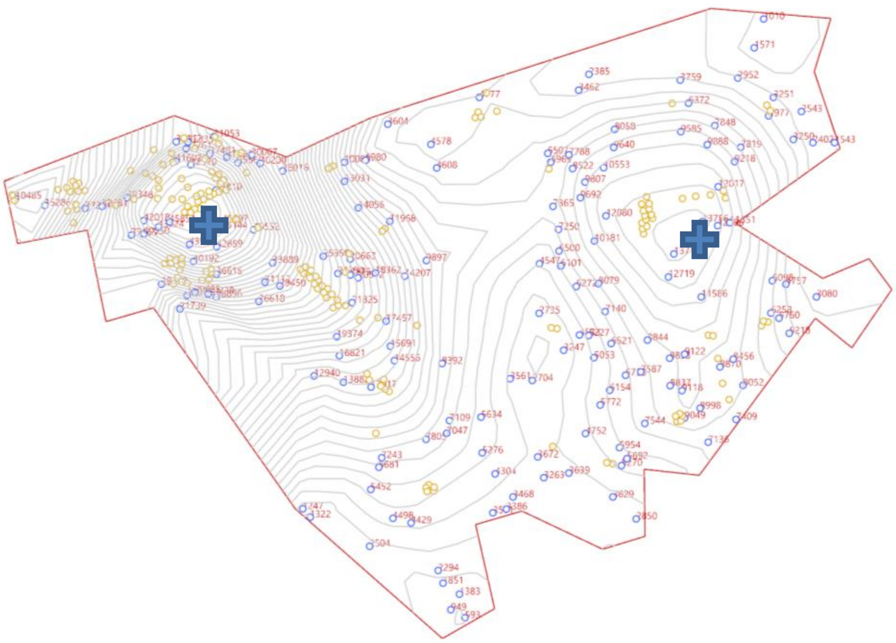

Figure 60 Cumulative opportunity measure of accessibility of home to shops reconstructed from Guy's comparison of cumulative opportunity measure and gravity measures. Peaks for higher values of accessibility indicated with a + sign

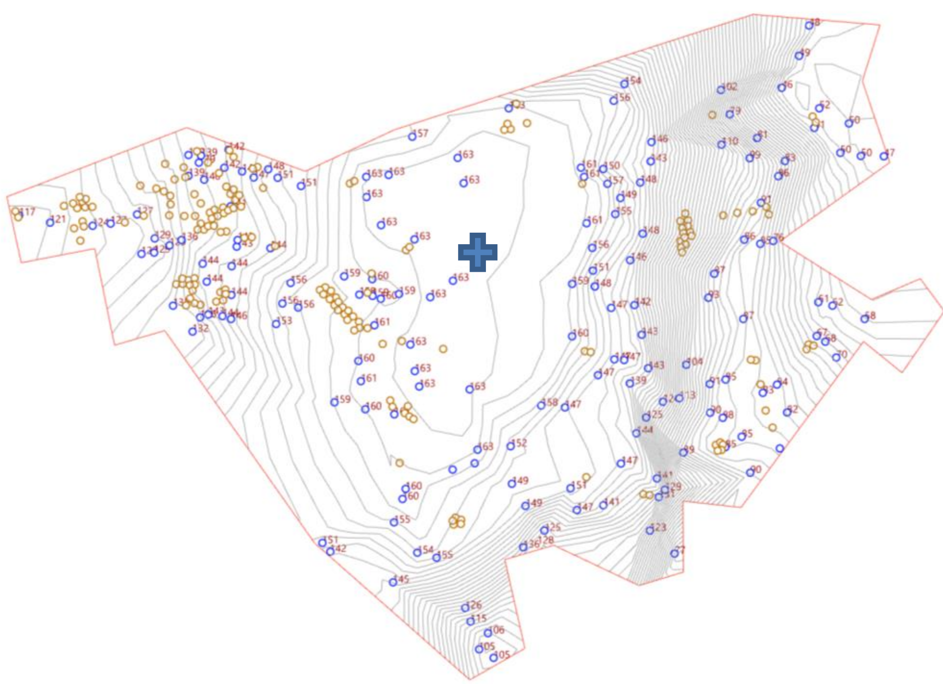

Figure 61 Measure created using the space time model developed in this study based on a simple activity program Home-Shop-Home. Peaks indicated with a + sign

Findings for construct discriminant validity

A visual comparison between two maps suggest the two measures are different as expected, a feature of space time based measures found in Kwan's (1998) comparative analysis of accessibility measures.

Cumulative opportunity measure favours concentration of shops in close proximity where the higher values of accessibility can be observed. A space time measure based on the number of shops possible for each household, however favours households that has more opportunities to reach different shops in different directions.

Limitations of the construct convergent comparison and discussions

While the two measures are setup in a way that is as similar as possible, there are inherent difference in the two setups. The first is that the cumulative opportunity measure used in this comparison is calculated based on straight line distances between opportunity (600m as used in the reference) while the space time measure as constructed in this study relies on time (10 minutes) between locations based on the street network.

5.5 Discussion (critical assessment and reflection)

This section discusses the analytical construct developed in this study. The first part describes the contribution to knowledge. The second part describes the limitations of the study

5.5.1 Contribution to knowledge

This study has a primary focus in methodological development where the potential of a space-time approach for scenario modelling and analysis on alternative urban conditions for city design is explored through a constructive research framework.

The main contribution to knowledge derives from the development of an analytical construct in two parts (1) an analytical framework to compare travel modes in alternative urban conditions (2) a space-time model within a time geography theoretical framework.

The process taken to develop the analytical construct and the analysis of the analytical construct developed leads to the identification of **implications for applied research** towards practical utility and **implications for fundamental research** towards epistemic utility.

5.5.1.1 Analytical construct as a contribution to knowledge

The space time model as part of the analytical construct developed in this study contributes to a theoretical body of knowledge in the time geography-based approaches. Time geography related approaches are explored in this study as a "kernel theory" that supports a space-time analytical approach for scenario analysis of alternative urban conditions.

Time geography has informed multiple areas of research (Ellegård and Svedin, 2012). The overlapping areas of research relevant to this study can be identified as four different groups: (1) human activity analysis (Shoval and Isaacson, 2007) (2) studies related to transport modelling with an emphasis on generating activity patterns (Timmermans, Arentze and C.-H. Joh, 2002b) (3) studies that extends the space-time approaches (Miller, 1991; Dijst, 1995; Kwan, 2004a) and (4) studies that applies space-time constructs (Dijst, de Jong and van Eck, 2002).

The research activities in this study mainly situates within the third area with the main body of work around **constructing a space-time model that extends previous work in multiple ways,** its potential use is demonstrated in the context of city design similar to the fourth area of studies. The potential use is facilitated by the **development of an analytical framework** that facilitate the translation of results from a space time model to an understanding of alternative urban conditions for city design.

The analysis of the analytical construct is discussed in two parts. The underlying space time model is tested for its similarities to similar model. The analytical framework is tested against other accessibility measures to highlight the differences.

5.5.1.2 Extension to previous work in space time model

Knowledge claim 1: Improved known method and model incorporating new technologies for the analysis of person-based accessibility in alternative urban conditions

Time-sensitive passenger services in activity-based space time model

The intersection between individual space time constraints as a connected sequence of activities and the space time constraints of the urban condition is central to a space time approach. Previous work has focused on the time-sensitive aspects of urban opportunities in terms of opening hours; one cannot perform a location-bound activity if the location is not open for use. This study attempts to introduce the inclusion of time-sensitive passenger transport services; one has little use for a passenger transport service when the timing of the passenger service does not match the timeframe required to get to a location to perform a location-bound activity. On a trip-by-trip basis this may be trivial, but is more complex when a connected sequence of activities is being considered.

The inclusion of new technologies in the inclusion of the opportunities for activity participation, transport network and public transport schedules is the main difference from previous space time models including MASTIC (Dijst, 1995) and PESASP (Lenntorp, 1976) that informed this study. The new underlying space time model is compared with Lenntorp's PESASP through a reconstruction of the Karlstad study using the new underlying space time model.

While the underlying goal of comparing the number of feasible activity programme towards an environmental perspective are the same, this study differs from closest related work in the applied level including Ritsema van Eck et al (2005) explorative simulation study and Dijst et al (Dijst, de Jong and van Eck, 2002) in Zoetermeer based on MASTIC because the focus is in developing the underlying space time model.

5.5.1.3 Contribution to knowledge in related contexts

Knowledge claim 2: Demonstrated application for the improved method in the context of opportunities for travel mode change in alternative urban conditions

This study demonstrates the use of a user-centric space time accessibility as a complimentary alternative to other accessibility measures towards an understanding of sustainable accessibility. There are many ways to facilitate an understanding of sustainable accessibility. This is in part due to the multiple ways "sustainability" can be conceived as well as the multiple ways "accessibility" can be assessed. Space time accessibility can be useful as a person-based accessibility measure where it is said to be different from other accessibility measures following Ingram (1971) conceptual comparison and Kwan (1998) statistical comparison of space time accessibility and other accessibility measures.

The extended space time model and the analytical framework developed in this study that can be used to produce different kinds of accessibility measures for purposes in applied domains such as comparison of public transport against other modes (Lenntorp, 1979) and accessibility measures for empirical studies (Kwan and Hong, 1998). This study explored "the usefulness of different accessibility measures for different planning purposes and concerns, with specific focus on sustainable development" (Silva and Larsson, 2018) with a focus on space-time measures through the development of an analytical framework for the comparison of travel modes sensitive to individual and urban space time constraints.

5.5.1.4 Implications for applied research

Knowledge claim 3: Shed some light on current analytical approaches for 'before the fact' analysis in relation to notions of sustainability relevant to travel activities in alternative urban conditions within built environments

It is necessary to investigate the analytical approaches to understand the conceptualisations and analytic tools for transport-integrated city design in academic literature. They reflect how land use and transport are thought about and understood across research fields. Different analytical approach and its associated concepts and theories supports different kinds of assessment and evaluation towards sustainability of transport system and travel activities. The formulation within the analytical approach is inextricably associated to certain kinds of interventions towards certain desirable goals.

This study identifies and compares three broad analytical approaches relevant to potential travel activities in alternative urban conditions. This is followed by the identification of the applicability for each analytical approach to understand different kinds of implications of alternative urban conditions towards sustainability of transport system and sustainable travel activities.

Research related to scenario analysis of alternative urban conditions commonly approach sustainability through the estimation of GHG emission with an estimated amount of transport activities. The analytical construct demonstrates an alternative way to understand the sustainability of transport system and the urban conditions to support more sustainable travel behaviour and practices.

Recontextualise underexplored space-time approaches for transport-integrated city design

Re-contextualise space-time approach for architecture as an alternative way to analyse and think about the possibilities of travel activities facilitated and constrained by spatial functions and transport infrastructure – elements commonly modified in the process of city design.

The current analytical approaches in transport-integrated city design for alternative urban conditions tends towards emphasis in enhancing local walkability. a space syntax approach in architectural city design is a dominant analytical approach when an analytical approach is used. A space syntax approach enables a normative analysis of the spatial distribution of pedestrian and vehicle traffic volumes based on theory of natural movement. The connection between space syntax and public transport are limited to the number of entry and exit from stops/stations and the pedestrian connections to and from stops/stations. Similarly, there are analytical approaches that employs metrics related to transit-oriented-development principles to aid city design (Lima *et al.*, 2016) focuses on connections between locations within a site and public transport stops/stations. While the enhancement of urban spaces for non-motorised travel modes are of importance, there are limited considerations of a city connected by public transport and car-based transport as well as non-motorised travel modes.

On a wider regional scale, current analytical approaches for alternative urban conditions relates to a body of literature on land use and transport interactions (LUTI). The spatial scale of analysis varies from macro (e.g. MARS) to more micro approaches (e.g. ILUTE). While a LUTI approach includes considerations in a city connected by public transport and car-based transport as well as non-motorised travel modes, the goal of modelling and analysis remains at a marco level.

This study explores this gap between the local and regional spatial unit of analysis apparent in current analytical constructs through the construction of an analytical framework to aid the comparison of travel modes in alternative urban condition for transport integrated city design.

Exploration of properties of the analytical construct in alternative urban condition

The properties of the analytical construct are explored through two experiments with an introduction of a new hypothetical condition. The reconfiguration of transport is explored with the introduction of a new passenger service e.g. a bus service and route within the model and the reconfiguration of urban opportunities is explored through the introduction of a new school within the analytical construct. The analytical construct enables the tentative identification of gaps in public transport in a baseline condition based on an activity programme.

5.5.1.5 Implications for fundamental research

The applied orientation of the analytical construct creates the link between specific types of fundamental research in studies of the elements that contributes to understand the functioning of cities (Batty, 2008b) and applied research for city design in general (Karimi, 2012) and more specifically with a space time approach (Pickup and Town, 1981; Ritsema van Eck, Burghouwt and Dijst, 2005).

The analytical construct based on a space time approach developed in this study can make use of fundamental research to enhance the definition of activity programmes. In an activity-based travel analysis perspective, daily activity programmes or patterns are closely related to travel activities.

Traditional transport studies usually focus on travel to work for commuting and by extension transport models and only accounts for residential and economic activities such as access to jobs and shops. The activity-based approach started in the 1980s (Jones, 1983; Fox, 1995) enables a more complex considerations in kinds of location-bound activities that can be modelled and analysed (Vilhelmson, 1999).

For an activity-based space time models or space time accessibility in general, there is need for a set of empirically informed activity sequences as the inputs. There are research developments in the methods to analyse activity patterns from compatible survey data (Shoval and Isaacson, 2007) and methods to generate of activity patterns from datasets towards travel demand modelling (TDM) (Timmermans, Arentze and C.-H. Joh, 2002b; Rasouli and Timmermans, 2014). The former is more relevant to this study where one branch of analysis produces categories of activity schedules as Representative Activity Pattern (RAP) (Recker, Mcnally and Root, 1985) for a specific dataset. RAPs provide a broad and general view in the types of ways people conduct daily activities reflecting a general pattern of time allocation to different activity location types.

There are known limitations in RAP, which has been further developed for analysis and methods towards TDM (Goulias, 2009). However, this branch of research activities towards TDM are generally data intensive for a specific localised context.

Thus, RAP remains a useful approach to activity-based analysis in two ways. Firstly, it is applicable when the specific data in the locality is scarce. Secondly, where the data collection would be impossible, for example, in a new urban development where there are no existing inhabitants or in an urban regeneration scheme where the majority of the potential inhabitants are yet to live in the area. RAP has been employed in a number of studies and method development as a basis for urban accessibility measures (Baradaran and Ramjerdi, 2001; Soo, Ettema and Ottens, 2009).

5.5.2 Limitations of this study

5.5.2.1 Limitation of a possibility-oriented approach

It is inherent in space time models and other accessibility-based approaches that they help to identify possibilities but limited in producing insight of the likely probable outcomes from an intervention. Probable outcomes of travel activities related to urban conditions are explored in metrics correlations at a macro pattern level and behavioural-oriented approaches at a micro level in transport-related studies.

It is worth noting that while space time models can be used to produce person-based accessibility measures, space time models differ from other accessibility measures in that it is known to be used to delineate choice set alternatives as part of individual travel decisions central to behavioural-oriented approaches. In this context, identifying the possibilities is an important prerequisite in identifying probabilities. An example is the inclusion of space time constraints in defining the choice set alternatives in a utility-based approach (Kitamura, 1997). Another example is Kwan's GISICAS (1994) use of a space time approach as part of a cognitive computation process based approach to micro travel decisions.

Similarly, while the modal structure of travel modes is important to assess the environmental sustainability of transport system, a possibility-oriented approach does not produce an estimation of modal split between different transport modes. A space time approach on its own is limited to investigations in the opportunities of mode change (Dijst, de Jong and van Eck, 2002) and the possibilities to conduct a series of location-bound daily activities by different travel modes (Lenntorp, 1978, 1979). However, it does provide an understanding of the "conditions beyond the individual" (Stern, 2000) as well as considerations of the individual through a combination of the facilitating and constraining conditions of the urban condition and individual's space time constraints.

5.5.2.2 Limitation of model, outputs and its interpretation

In this study, while the space time model includes four elements and their relationships, the model can only produce insight on what is included as the urban condition in the applied level. This includes the geographic data of the road and street network, the public transport service schedules, the activity programme and the opportunities for activity participation. The outputs are sensitive to all four components therefore they can only be interpreted in relative terms by comparing alternative condition against a defined baseline condition. In addition, the comparison of travel mode in this study assumes all the journey has to be conducted by the same type of travel mode. This can be specified in a different way to reflect the different ways in which travel modes can be mixed within a daily activity programme.

5.5.2.3 Road traffic conditions and public transport delays

Road traffic and delays in public transport is not included in this study but can be included if there are generalisation of daily traffic volumes over time or from models that estimates traffic volumes per road segment. Because road traffic, public transport reliability is not included the access to urban opportunities, it is expected that the reach to urban opportunities within a timeframe is likely to be an overestimate.

There are limitations in computational tractability in the approach to space time model in this study. Computational more tractable is a common concern for the practicality for the algorithmic process to run in reasonable time for space time approaches (Kwan, 1998; Miller and Bridwell, 2009). The analytical construct is developed mainly for the purpose to identify implications for applied and fundamental research. analytical procedure can be optimised for practical use with further development.

5.5.2.4 Activity programme

Although the inclusion of individual activity programme enables the model to be sensitive to the differences and circumstances for individuals or groups in the population, it poses a major data challenge to obtain detailed data for a specific context. The limitation in this study is the use of normative daily activity programmes as oppose to a data driven approach to activity schedules, sequence or pattern. An attempt has been made within this study in the appendix section to understand more about empirically driven activity sequences.

This study frames activity programmes within a day, which is typical in the related studies commonly referred to as “daily activity programme” (Fox, 1995). The normative activity programmes examples devised for the experiments in this study refers to a specific case of a typical work day with the need to bring a child to and back from school. Different set of patterns for a work day and a non-work day is expected where the workplace or the schools are closed and other location-bound activities are sought on a non-work day.

In the context of activity-based travel modelling and analysis, models that focuses on the connection between activity programme and urban condition such as PESASP and MASTIC are classed as “constraint-based models”. Most recent models within the research area focuses on the generation of activity patterns with two variations “utility-based” or “computation process-based”. This study orients towards the “constraint-based models” with more emphasis on the urban condition.

5.5.2.5 Gaps in public transport

In the context of locating gaps in public transport, the approach taken in this study differs from approaches such as PTAL or GMAL that provides an understanding of the overall coverage of public transport. The approach taken in this study can only identify gaps for a specific use case or a set of use cases due to the nature of a space-time model driven by an activity programme. Nonetheless the approach has the potential to contribute to a more detailed understanding of which gap needs to be filled and whether the proposed public transport enhances the connectivity between urban opportunities that are visited as part of everyday life in conjunction with other methods.

5.5.2.6 The question of location-bound activities

Although the connection between spatial functions and location-bound activities as opportunities for activity participation has been a common assumption as a basis for travel patterns between locations. There are observations of contemporary societies in literature that suggests otherwise. The main relevant topic to the amount of travel activities is the role of ICT in reducing the amount of travel activities especially in telecommuting which reduces the need for work to be location-bound. There are authors that argues for and develops time geography-based approach in transport-related studies as a useful approach given the wider shift towards ICT.

The discussion around absolute, relative and relational space is also a relevant topic (Dijst, 2018). However, the study based on travel patterns between locations that is aimed at understanding the implications of allocation of spatial functions and transport service provision primarily deals with the functional and operational aspect of city where an absolute or relative conception of physical space is necessary. In this context, the study is limited in the absolute and relative conceptualisation of space. The need to include understanding of relational space is acknowledged.

5.5.2.7 Other theoretical criticisms

Although time geography as an approach in human geography has been criticised as “physicalism” and “more related to physical science than to social science” (Hallin, 1991), it is the “physical theory” aspect of a space-time approach that is of relevance in this study - the city design and plan making are fundamentally about physical space and service planning. The role of spatial organisation in shaping individual accessibility has been a topic for research for city design (Scott and Horner, 2008) with accessibility constructs supporting collaborative plan making process (Bertolini, le Clercq and Kapoen, 2005). They typically employ location-based accessibility, but the process can be benefit from the additional consideration of the temporal dimensions (Neutens, Schwanen and Witlox, 2011) and person-based considerations (Miller, 2005) supported by a space-time approach.

5.5.2.8 Space time accessibility

The reason why Hansen’s formulation of a gravity-based accessibility measure (Hansen, 1959) is typically used in land use transport integrated models is because the accessibility measure has been used to correlate with household location choice. This supports a theory that the specific formulation of accessibility connects transport and land use. This study focuses on the space time model that can produce measures of space time accessibility. In order to contribute to a micro variation of the “land use transport feedback cycle”, further studies are required to find whether there are relationships between the measures of space time accessibility and characteristics of land use. Especially in connection with agent-based modelling approaches typically considers outcomes from the decisions of individuals as oppose to the outcomes from spatial interactions.

Although there are advantages in adopting a space time approach to accessibility, it is a challenge to apply. In a review of the use of accessibility measures to study housing, Heyman et al points out there are currently very limited studies that applies individual accessibility including utility-based and space time-based accessibility for the particular topic within their sampled literature and further suggests that it is “likely due to the need of heavy analytical efforts” (Heyman, Law and Berghauser Pont, 2018). This is related to the previous discussion in the data challenge but also the availability of space time models. Space-time accessibility relies on analytical constructs that is highly specialised with “increasingly complex algorithms” (Kwan and Hong, 1998; Kwan, 2004a; Neutens, Schwanen and Witlox, 2011). This study attempts to reintroduce space time model in the context of city design is just a beginning of the wider research challenges.

5.6 Further work

This section highlights further research in 1) the potential use cases to conduct an ex-ante analysis of alternative urban conditions with the analytical construct, 2) the potential extensions on the analytical construct to further extend the details embedded within the implementation, 3) the fundamental research that could be conducted to enhance certain aspects for the analytical construct and 4) the analytical construct in a wider research context with other known domains of research.

5.6.1 With the analytical construct

This study has been informed by Dijst et al. (2002) exploratory study towards an analysis of the opportunities for travel mode change as an application of the underlying space-time model. There is a need for further work to test and refine the analytical construct both of the analytical framework and the underlying computational model and method through applied study in a specific urban context. Previous studies have demonstrated the ability for the underlying space-time model for use in an applied urban context, answering different applied-oriented questions with different conceptualisations of the analytical framework supported by the underlying computational model and methods (Lenntorp, 1979; Pickup & Town, 1981; Ritsema van Eck et al., 2005).

A more concrete example of the analytical construct's potential use case is its application in participatory models to elicit the implications of spatiotemporal changes in the inhabitant's everyday life. A space-time based participatory model had been explored previously by Jones (1980). This study provides a technological update of the underlying space-time operational model in line with the recent development and wide adaptation of web-based mapping services and digital journey planner. The analytical construct from this study can be built in as part of interactive scenarios. The geospatial interface can be visualised similar to web-based mapping services and digital journey planner but differ from existing services in the underlying data based on alternative urban conditions. As part of interactive scenarios, the analytical construct enables users to understand the relative differences and impact of everyday activities under different urban conditions configurations. For example, the benefits or impedance to a sequence of daily activities resulted in a change in bus timetables, and routes can be compared to conditions without modification. The proposed changes in alternative urban conditions can be further analysed based on collecting daily activities from different population groups for questions such as who benefits and possible disadvantages to certain groups due to the proposed alternative urban conditions.

One of the properties of a space-time approach is the ability to include joint activities. This has previously been explored by Neutens et al. (2007; 2008) to reveal the potential interaction space given two sequences of daily schedules. Along this line of thought, one can extend the methodological toolset to help understand residential location choice considering joint activities from household members. An example is the sample case explored in the case study experiment within this thesis of an adult bringing a child to and from school or nursery whilst travelling to and from work. Considering the possible changes in the commuting pattern in the future that could be resulted from the widespread use of remote work under lockdown measures to reduce recent pandemic spread, it is of interest to investigate whether there are also changes to residential location choice patterns. In this context, a space-time approach and the notion of joint activities may contribute from a perspective that includes the fundamental considerations from members within a household. For example, when one adult in a household can work remotely, while another member in the same household has to travel to work or school physically.

Although the space-time model is conceived with a focus on the movement of people based on everyday activity schedules and sequences are closely coupled with definitions of opportunities for activity participation such as schools, nursery, clinics, hospitals, workplace, there is scope for the model to incorporate other related topics. A potential trajectory for exploration is the movement of goods, for example, in groceries and food delivery. There are temporal requirements, entities, and people involved within the delivery chain from the source where and when food is produced and the end-users. For example, food delivery services such as Dominos, Deliveroo and UberEAT requires someone to be at the right place at the right time for the pickup and delivery of food products. The spatiotemporal positions of people and products involved can be formulated as activity schedules and sequences. The space-time paths of each element involved in the service can be simulated for operational planning purposes or monitored for empirical data analysis. A further extension is the implications of alternative urban conditions to specific types of food delivery services or to analyses the competitions amongst services. In particular, when they employ different travel modes such as vans, motorbikes and bicycles for delivery, each with different spatiotemporal constraints facilitated and constrained by the built environment.

5.6.2 Within the analytical construct

Extensions can be made to the extended space-time model documented in section 5.2 pg156-179 with specific technical prerequisites highlighted in section 5.2.5.5 pg177. It is intended for the algorithmic components to be packaged and released open-source online for others to use, modify, extend, and adapt the analytical construct for specific use case.

It is possible for the current implementation of the analytical construct to explore most kinds of road and rail-based passenger transport modes with planned time schedules such as buses, trams and trains with minimal adaptation of the underlying model in this study. Additional work can adapt the underlying model to work with schedules that are not as fixed, such as demand responsive services where routes and time schedules are planned in a shorter time span. Because the model is able to work with multiple passenger travel modes, it is also possible to investigate the competition between different passenger travel modes.

Additional details and specific characteristics of each travel mode can be included in the model. For example, the need for car parking space in a car-based trip can be included which can produce a more realistic representation of car-based trips which does not often go door-to-door especially when the destination is in a city centre location. There are also implications on private car parking requirements in residential developments from planning in a UK context. Similarly, the facilities and infrastructure that facilitates cycling can be incorporated. The effect of road traffic on travel time is also an important aspect that can be further explored.

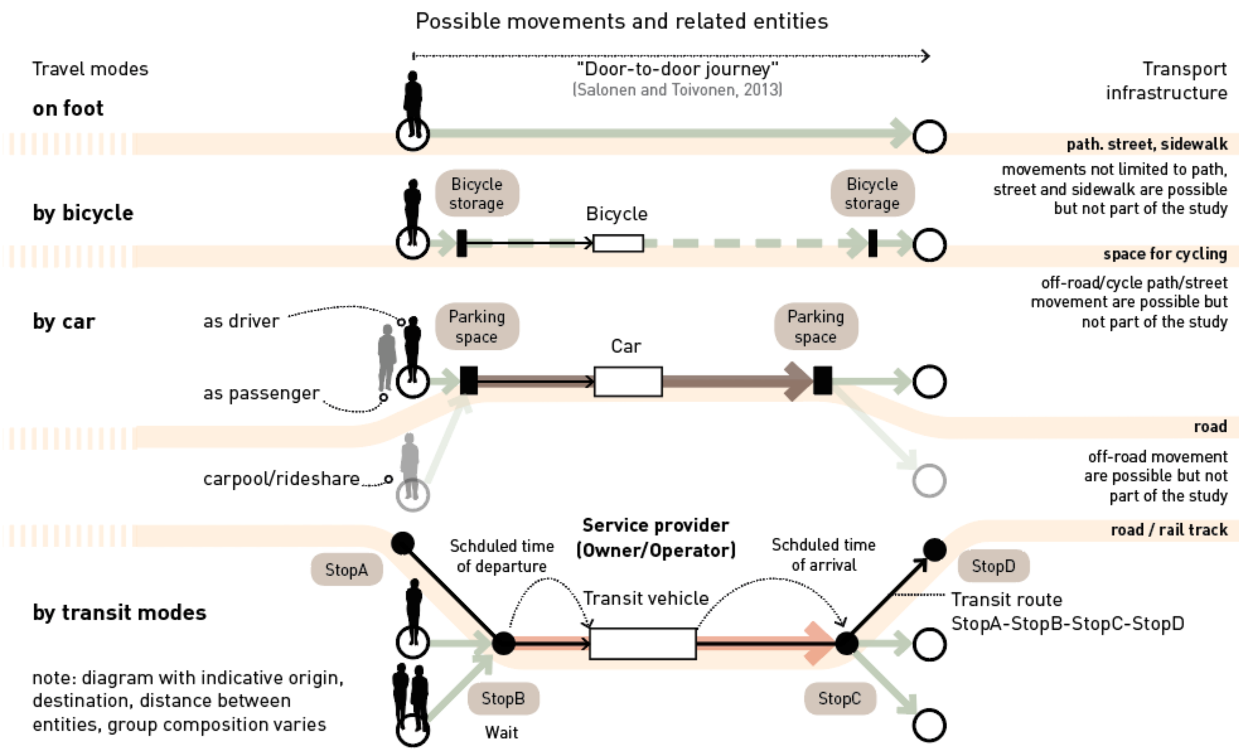

Figure 62 characteristics unique to each travel mode

5.6.3 For the analytical construct

As mentioned in the implications for fundamental research section 5.5.1.5 pg201, there is a need to explore the human activity pattern side of space time models. An attempt was made in this study which can be found in the appendix section. The analysis of human activity pattern in relation to travel activities is more developed in the activity-based travel analysis field of research and human activity analysis is an area of study that deals with time use allocation and studies of patterns in social sequence (Abbott, 1995; Shoval and Isaacson, 2007; Cornwell, 2015).

On the same line of thought, the need to acquire data for a space time approach is a major challenge. Although the privacy concerns are a major issue, the growth of Global Position Systems (GPS) in everyday use has increase the possibilities to acquire data for a data driven approach to modelling activity patterns. Miller suggests there are potentials for a time geographic approach to add semantics to GPS data given the recent technological advancements and adaptation of GPS enabled devices (Miller, 2017a).

The other opportunity for further work is the definition of opportunities for activity participation within a computer model in a constantly changing world. Although in this study the spatial functions of locations are used as a proxy for location-bound activities, space time models similar to the one developed and explored in this study can benefit from approaches that empirically analyses or non-empirically generates different types of emergent opportunities for activity participation beyond the land use or building use classifications in relation to the types of activities from time use or travel survey used in this study.

5.6.4 In a wider research context

A space time approach to land use and transport contributes to the discussion in the trend in wider academic literature of micro variations in transport, accessibility and land use within the “land use transport feedback cycle” (M Wegener, 2004). The development of a space time model that is can be operated by a wider audience may help in reducing the barrier for the application of space time approaches in other studies due “the need of heavy analytical efforts” (Heyman, Law and Berghauser Pont, 2018) through the “ease of implementation” for an analytical construct that is highly specialised with “increasingly complex algorithms” (Neutens, Schwanen and Witlox, 2011).

Theoretically, there are calls to develop time geography approaches in multiple ways (Sui, 2012). There are opportunities to further advance the more physical aspects of a space-time analytical approach to complement current lines of social studies-oriented theoretical development in the context of human mobility (Sui, 2012) – including a complexity perspective (Ellegård, 1999) and social practice theories (Vrotsou, Johansson and Cooper, 2009; Mattioli, Anable and Vrotsou, 2016).

5.7 Conclusion

The computation enabled analytical construct developed in this study fills a gap in a specific niche in the applied analysis and assessment of alternative urban condition towards sustainability of transport integrated city design. As part of the analytical construct, a computation enabled analytical framework has been developed to understand the implications of alternative urban conditions on travel mode possibilities based on individual’s space and time constraints. Specific attention has been placed on the comparison between passenger transport services and personal travel modes as it is a challenge to provide services that has environmental impact yet beneficial to the social and economic dimensions of sustainability.

A space time approach is adopted in this study based on the work from Lenntorp and Dijst, which enables the consideration of both a spatio-temporal and an environmental perspective. Space time model enables the investigation and analysis of alternative urban conditions. Lenntorp’s PESASP is a space time model developed (Lenntorp, 1976) and applied in studies of travel modes possibilities in the city of Karlstad (Lenntorp, 1978) and the city of Orebro (Lenntorp, 1979). Dijst’s MASTIC (Dijst, 1995) was developed in 1995 and subsequently applied in the study of mode change opportunities (Dijst, de Jong and van Eck, 2002) and explorative simulation study of spatial configuration in the city of Zoetemeer (Ritsema van Eck, Burghouwt and Dijst, 2005).

The underlying space time model has informed other studies on the development of different types of space time models for different purposes. These developments have advanced the general field of space time approaches. Most notably the formulation of space time accessibility as a measure (Villoria, 1989), the introduction of transport network as network-time prism (Miller, 1991), the integration with GIS (Kwan and Hong, 1998), the introduction of joint accessibility (Neutens *et al.*, 2007) and the introduction of space time constructs in commercial GIS (Charleux, 2015). While there is advancement in variations of space time model for the study of existing urban conditions, the simulative space time model for alternative urban conditions such as PESASP and MASTIC is underdeveloped.

The main contribution of this study is the further development of the underlying computational space time model with specific considerations in its use for alternative urban conditions. The underlying theoretical construct is largely informed by the previous work of PESASP and MASTIC but the implementation is different and informed by advancements in related studies. One of the main extensions in this study compared to the previous similar space time model is the digital model of the transport network fundamental in the computation of possible reach between opportunities. This study incorporates the constantly evolving and open-sourced OpenTripPlanner as a multimodal router for a specific part for travel analysis in the overall algorithmic procedure, this has been mentioned in related studies (Charleux, 2015) but to my knowledge it has not been achieved before for space time models. The use of a multimodal router within a process enables the investigation of time-sensitive passenger transport services. The possibilities to edit the passenger transport services, the road and street network with attributes for specific restrictions such as vehicle type and speed limit as inputs to the model are demonstrated with a set of custom tools in this study. The space time model developed in this study is compared with the similar construct PESASP for construct convergent validity through the reconstruction of its application in the study of Karlstad.

In the wider research context, this study has demonstrated an attempt to bridge the applied needs of transport-integrated city design and the possibilities for fundamental research to inform applied research with the development of method in the form of a computational analytical construct. The analytical approach adopted enables wider theoretical connections to other relevant established fields of study including geocomputation (Kwan, 2004b) and its application in empirical social studies (Kwan, 2013), land use transport in particular activity-based travel analysis (Timmermans, Arentze and C. Joh, 2002) and human activity analysis (Shoval and Isaacson, 2007).

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Appendix

Understanding activity programmes through time use data

In order to identify the types of activities derived from travel activities beyond commuting and the access to economic opportunities, a secondary analysis is performed on a UK time use data set to empirically inform the activity programme to aid the exploration and development of the analytical construct.

Time use data

The data source for the basis of activity programmes is UK time use diaries 2014-2015.

Uktus15_diary_wide.tab

Time use code (wher1)	Description	Time use code (act1)	Description	Short code
10	Unspecified location (not travelling)			X
11	Home			H
12	Second home or weekend house			H2
13	Working place or school			W
		2110-2190	Study	Sc (1300)
14	Other peoples home			Ho
15	Restaurant café or pub			E
16	Sports facility			Sp
17	Arts or cultural centre			AC
18	Parks countryside seaside beach or coast			P
19	Shopping centres markets other shops			Sh
20	Hotel guesthouse camping site			G
21	Other specified location (not travelling)			X

Description of data

Total observations (rows in dataset): 16533
Total observations for work day (tagged in KindOfDay 1 or 2): 5116

Re-formatted data for analysis example

sequence index 11
short sequence ['11', '90', '38', '13', '38', '11']

short sequence duration [15, 3, 2, 58, 6, 60]
location only short sequence ['11', '13', '11']
location only short sequence duration [15, 58, 60]
location only short sequence shortcode H-W-H
long sequence ['11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'90', '90', '90', '38', '38', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13',
'13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13',
'13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13',
'13', '13', '13', '13', '13', '13', '38', '38', '38', '38', '38', '38', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11']
serial 11011213

sequence index 38
short sequence ['11', '34', '13', '34', '11']
short sequence duration [42, 3, 43, 2, 54]
location only short sequence ['11', '13', '11']
location only short sequence duration [42, 43, 54]
location only short sequence shortcode H-W-H
long sequence ['11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '34', '34', '34', '13', '13', '13', '13', '13', '13', '13', '13',
'13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13',
'13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '13', '34', '34', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11',
'11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11', '11']
serial 11020611

Time use data for analysis example

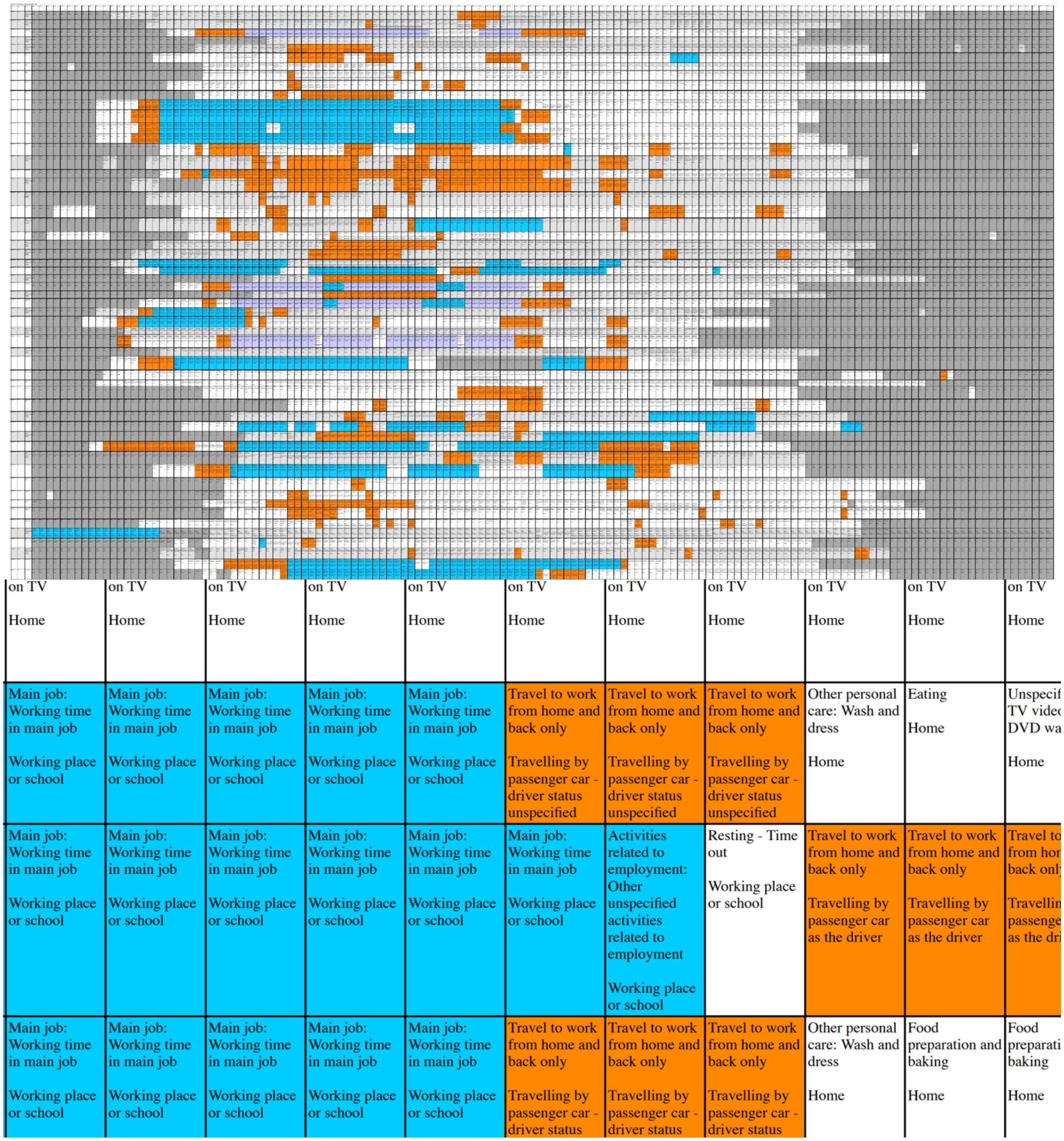


Figure X. UK time use diaries 2014-2015, own visualisation

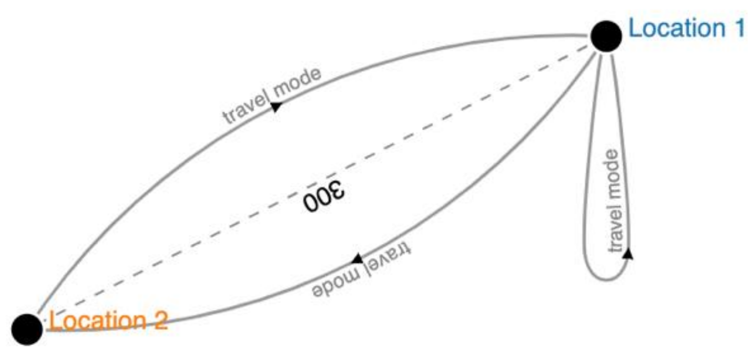


Figure X. Specification of topological representation derived from characteristics in time use diary. Includes undirected travel activities.

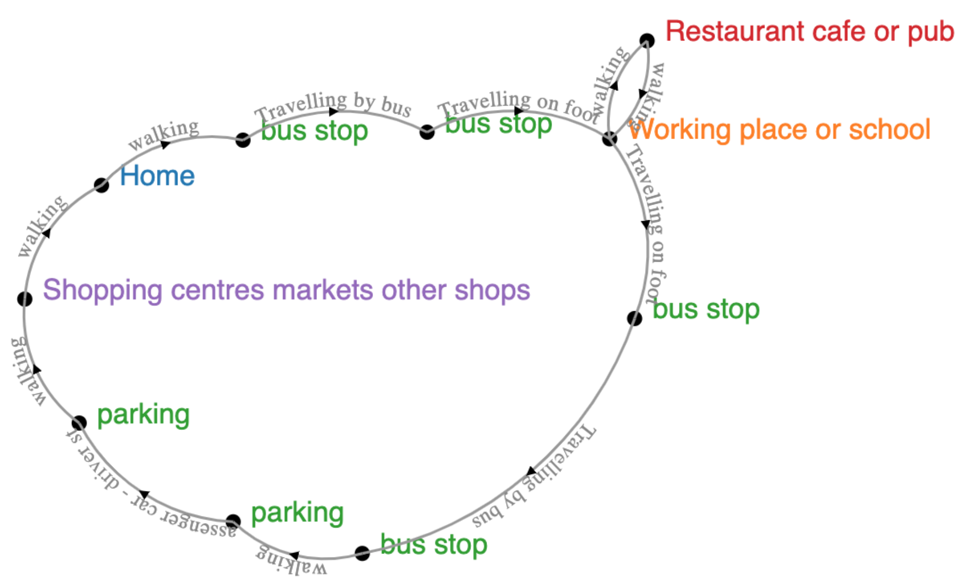


Figure X. Example of one observation within the time use diary

Cluster analysis

The aim is to find a number of Representative Activity Patterns (RAP) for the next stage in an analytical framework to compare accessibility by different travel modes.

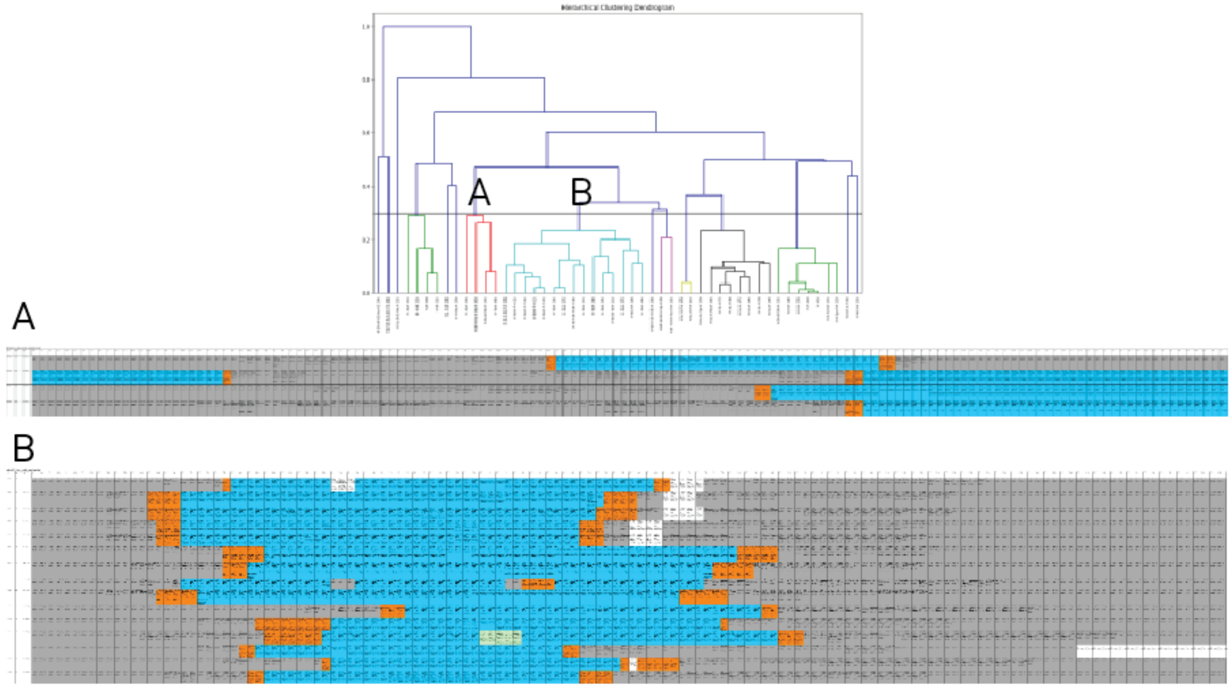
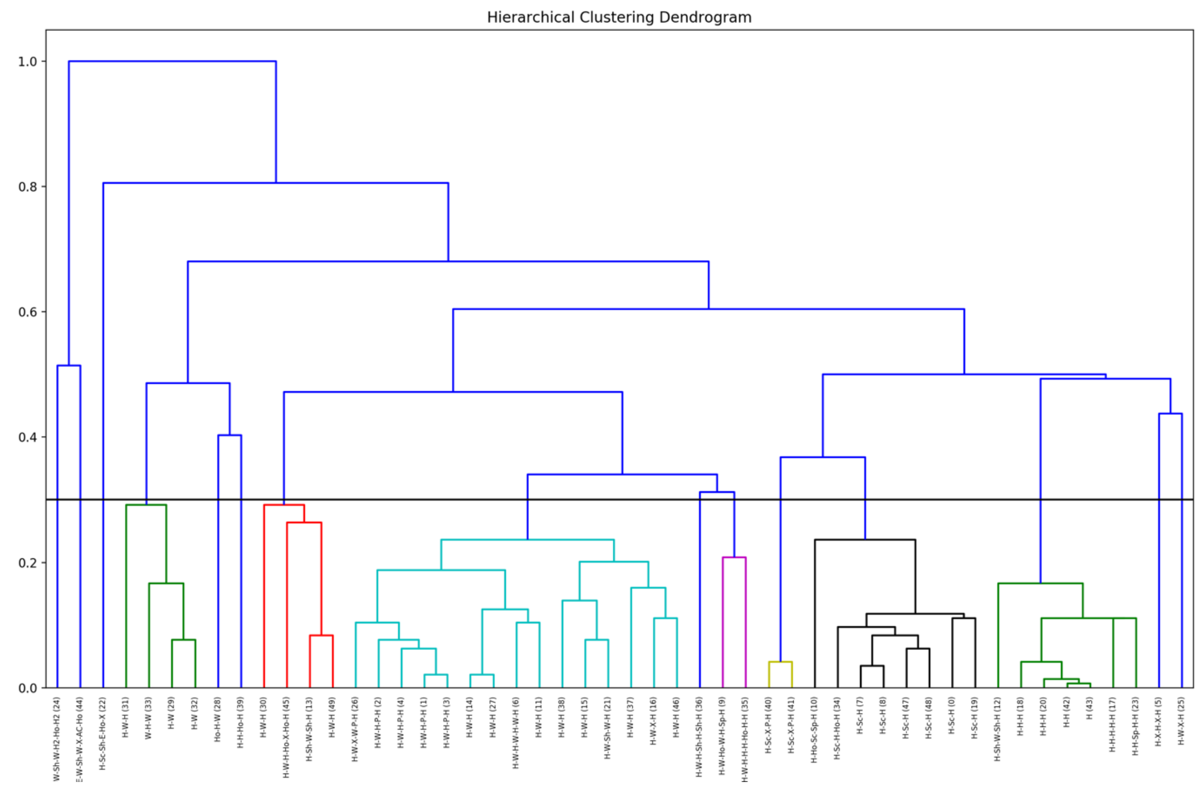
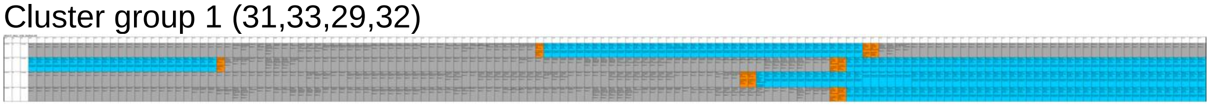


Figure X. grouping similar sequences using cluster analysis UK time use diaries 2014-2015, own visualisation

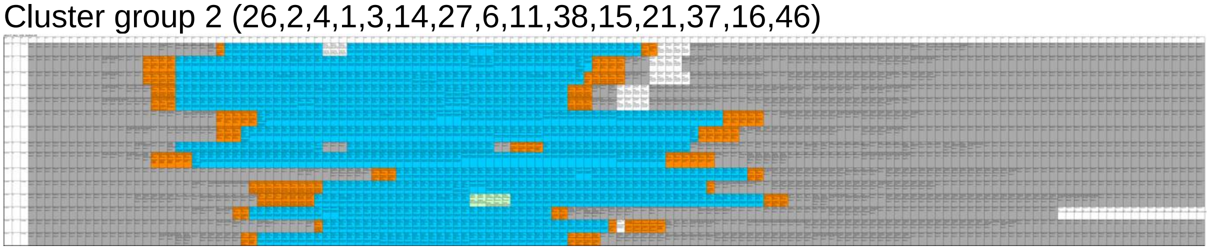
First test
sequence_cluster_analysis_test1.py
An initial test using metric Longest Common Sequence (LCS) for similarity distance measure between observations:



Cluster group 1 (31,33,29,32)

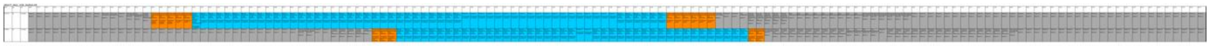


Cluster group 2 (26,2,4,1,3,14,27,6,11,38,15,21,37,16,46)



Observation 31 appears odd in the cluster group 1 which is more similar to observation 38 in cluster group 2.

Observation(11) and observation(38)



Although observation (31) and the cluster group contains similar sequence of activity locations types (H-W-H) the allocation across the time is significantly different between observation 11 and observation 31 (see figure below) but similar to observation 38 (figure above).

Second test
sequence_cluster_analysis_test2.py

Given that the objective is (1) **to find categories by sequence of activity location types** and to find the (2) **time variations within the same class of activity pattern**, a different strategy is tested.

The second test begins with the identification of **unique sequences of activity location type** from the short sequences without duration.

0 H-Sc-H
1 H-W-H-P-H
2 H-W-H-P-H
3 H-W-H-P-H
4 H-W-H-P-H
~~5 H-X-H-X-H~~
6 H-W-H-W-H-W-H
7 H-Sc-H
8 H-Sc-H
9 H-W-Ho-W-H-Sp-H
10 H-Ho-Sc-Sp-H
11 H-W-H
12 H-Sh-W-Sh-H
13 H-Sh-W-Sh-H
14 H-W-H
15 H-W-H
~~16 H-W-X-H~~
~~17 H-H-H-H-H~~
~~18 H-H-H~~
19 H-Sc-H
~~20 H-H-H~~
21 H-W-Sh-W-H
~~22 H-Sc-Sh-E-Ho-X~~
23 H-H-Sp-H-H
24 H2-W-Sh-W-H2-Ho-H2
~~25 H-W-X-H~~
~~26 H-W-X-W-P-H~~
27 H-W-H
28 Ho-H-W

29 H-W
30 H-W-H
31 H-W-H
32 H-W
33 W-H-W
34 H-Sc-H-Ho-H
35 H-W-H-H-H-Ho-H-H
36 H-W-H-Sh-H-Sh-H
37 H-W-H
38 H-W-H
39 H-H-Ho-H
~~40 H-Sc-X-P-H~~
~~41 H-Sc-X-P-H~~
~~42 H-H~~
~~43 H~~
~~44 H-E-W-E-W-Sh-W-X-AC-Ho~~
~~45 H-W-H-Ho-X-Ho-H~~
46 H-W-H
47 H-Sc-H
48 H-Sc-H
49 H-W-H

Excluded
Travel activities that are not affected by the spatial distribution of opportunities for activity participation. For example, 42 H-H, 43 H, 17 H-H-H-H-H, 18 H-H-H etc.

Another set that contains “other specified locations” (21) without specific types and “No answer/refuced” (-9). For example, 25 H-W-X-H, 26 H-W-X-W-P-H, 44 H-E-W-E-W-Sh-W-X-AC-Ho etc.

H-H-Sp-H-H count: 1
H-W-H count: 10
W-H-W count: 1
H-W-H-H-H-Ho-H-H count: 1
H-Ho-Sc-Sp-H count: 1
H-W-H-P-H count: 4
H-Sh-W-Sh-H count: 2
H2-W-Sh-W-H2-Ho-H2 count: 1
H-W-H-Sh-H-Sh-H count: 1
Ho-H-W count: 1
H-Sc-H count: 6
H-W count: 2
(Filtered) count: 14
H-Sc-H-Ho-H count: 1
H-W-Sh-W-H count: 1
H-H-Ho-H count: 1

H-W-Ho-W-H-Sp-H count: 1
H-W-H-W-H-W-H count: 1

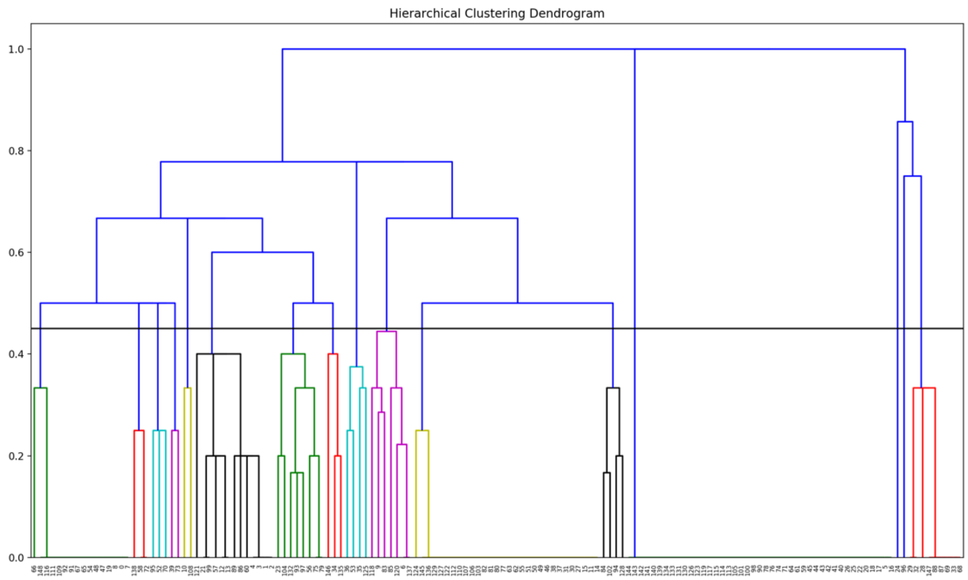
total groups: 18
total observations: 50

Executing the above procedure over 5116 observations related to workday yields 923 groups. A sample of groups with over 10 occurrences is shown below.

H-W-H count: 853
H-Sc-H count: 307
H-W-H-H count: 120
H-W-W-H count: 106
H-W-Sh-H count: 70
H-W-H-Ho-H count: 58
H-W-H-W-H count: 57
H-W-H-Sp-H count: 52
H-H-W-H count: 50
H-W-Ho-H count: 40
H-W-H-Sh-H count: 40
W-H-W count: 39
H-Sc-H-H count: 39
H-W-H-E-H count: 38
H-W-E-W-H count: 37
H-W-Sh-W-H count: 37
H-Sc-H-Sp-H count: 36
H-Sh-H count: 36
H-Sc-Ho-H count: 25
H-W-W-W-H count: 23
H-W-W-H-H count: 22
H-W-E-H count: 21
H-Sc-H-Ho-H count: 21
H-W-H-H-H count: 21
H-W-Sp-H count: 20
H-W count: 18
H-Sc-H-P-H count: 18
H-W-H-P-H count: 17
H-W-W-Sh-H count: 16
H-Sh-W-H count: 16
H-Sc-H-Sc-H count: 15
H-Ho-H count: 15
H-Sh-H-W-H count: 14
H-H-W-H-H count: 14
H-E-H count: 13
H-W-W-H-E-H count: 12
H-Sc-Sh-H count: 11

Third test
sequence_cluster_analysis_test3.py

Given the large number of groups - 923 groups over 5116 observations and most groups has only one sequence, the third test attempts to cluster similar sequences into larger general groups using methods in the first test.



On 50 samples with filtered short sequence
sequence_cluster_analysis_test3.py

Samples from clusters

cluster 29
129 H-W-H
136 H-W-H
145 H-W-H

cluster 30
124 H-W-Sp-H

cluster 16
93 H-H-W-W-H-H
97 H-H-W-H-Sp-H
132 H-H-W-H-H

sequence_cluster_analysis_test3a.py

There are similarities between a number of groups from second test, for example:
129 H-W-H (cluster 29)
93 H-H-W-W-H-H (cluster 16)
132 H-H-W-H-H (cluster 16)

The next test is to combine consecutive location types that are the same. For example, **sequence** 93: H-H-W-W-H-H with associated **duration** as counts of 10 minutes interval for each element.
Procedure:

1. take first item from sequence insert in stack 1, take first item from duration insert in stack 2
2. check the next element in sequence check if it matches the last element in stack 1
3. if matches then add next element in duration to last element in stack 2 (combine durations)
4. if there are no matches then add next element in sequence in stack 1 and next element in duration in stack 2

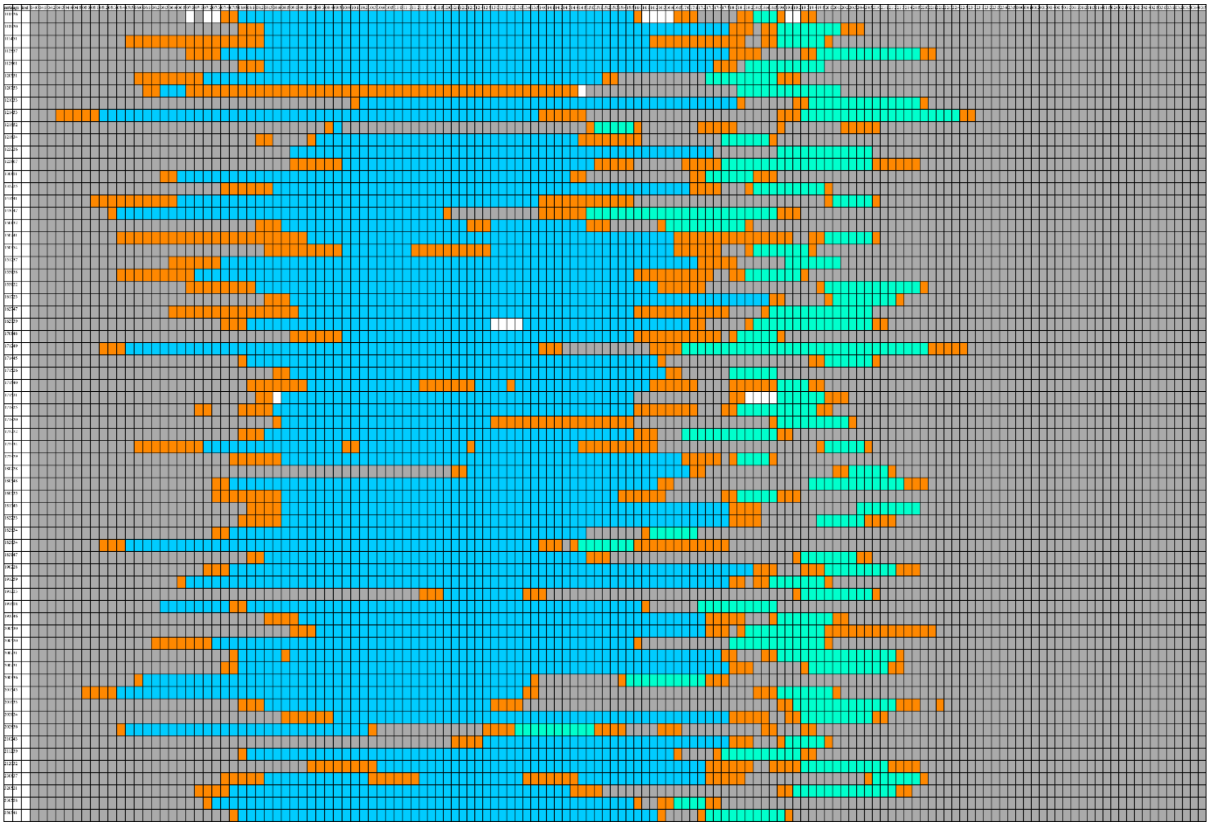
After combining the sequences, the procedure from test 2 is used to find the unique sequences.

Unique sequences for 50 samples:
H-W-H count: 10
W-H-W count: 1
H-Sp-H count: 1
H-Ho-H count: 1
H-Ho-Sc-Sp-H count: 1
H-W-H-P-H count: 4
H-Sh-W-Sh-H count: 2
H2-W-Sh-W-H2-Ho-H2 count: 1
H-W-H-Sh-H-Sh-H count: 1
Ho-H-W count: 1
H-Sc-H count: 6
H-W count: 2
(filtered) count: 14
H-W-H-Ho-H count: 1
H-Sc-H-Ho-H count: 1
H-W-Sh-W-H count: 1
H-W-Ho-W-H-Sp-H count: 1
H-W-H-W-H-W-H count: 1
total groups: 18
total observations: 50

Unique sequences for 5116 observations
total groups: 554
total observations: 5116

Sequences with more than 10 observations:
H-W-H 1187
H-Sc-H 349
H-W-Sh-H 104
H-W-H-W-H 80
H-W-H-Ho-H 75
H-W-H-Sp-H 66
H-Sh-H 61
H-W-H-E-H 57
H-W-Ho-H 54
H-W-E-W-H 53
H-W-H-Sh-H 46
H-W-Sh-W-H 46
W-H-W 44
H-Sc-H-Sp-H 38
H-Sc-Ho-H 33
H-W-E-H 31
H-W-Sp-H 31
H-Ho-H 28
H-Sc-H-Ho-H 27
H-W 21
H-P-H 21
H-W-H-P-H 20
H-Sc-H-P-H 19
H-Sh-W-H 19
H-E-H 19
H-Sh-H-W-H 19
H-Sc-H-Sc-H 19
H-Sp-H 17
H-Sc-Sh-H 15
H-W-H-W-H-W-H 14
H-E-W-H 14
W-H 11

Example of H-W-H-Sp-H sequence and its time variations



Literature review: analytical constructs

	Name	Full name	Year	Main Purpose	Space-related	People-related	Theory	Main characteristics	Technical notes	Main output(s)	Targeted application area(s)?
1	SUMO	Simulation of Urban Mobility	2001	Travel demand and traffic analysis	Road-based with TAZ	O-D matrix and (Route choice)	In general, limited space with a number of vehicles	Traffic simulation framework / Travel demand model	Open source framework	Framework for use in development of context-specific transport planning models	Predict travel demand and transport related measures e.g. traffic volume, flow
2	MATSIM	Multi-Agent Transport simulation	2008	Traffic analysis	Road-based and Public transport	Activity plan (pattern) and (Route choice, takes into account decision making units)	In general, limited space with a number of people driving in vehicles, iterative route re-planning due to external circumstances e.g. traffic.	Traffic simulation framework	Open source framework	Framework for use in development of context-specific transport planning models	Predict travel demand and transport related measures e.g. traffic volume, flow
3	MARS	Metropolitan Activity Relocation Simulator	2003	Interactions between multiple urban systems with feedback loops	TAZ based	Mode choice (amongst other models)	Spatial interaction-based trip generation, trip distrubution and mode choice based on entropy-maximization.	Land use transport integrated framework	Implemented in VENSIM	Case study demonstrated ability to produce a predictve baseline "within reasonable accuracy" based on historical data	Towards urban policy strategies towards the objective of sustainability
4	LUTDMM	Land Use, Travel Demand Microsimulaton Model	2005	Travel demand model	TAZ based	Activity pattern (choice)	Activity pattern is influenced by various factors including the built environment	Prototype of a Land use transport integrated framework	Not publicly avaliable	Implications of test scenarios demonstrates change in land use pattern result in changes in activity and travel pattern	Towards transport policy strategies
5	FEATHERS	Forecasting Evolutionary Activity-Travel of Household and their Environmental Repercussion	2007	Travel demand model	Transport network	Agent-based	Activity pattern is influenced by various factors including the built environment	Activity, Agent-based model framework	uses ALBATROSS for activity pattern generation	Travel demand in Flanders, Belgium	Towards transport policy strategies

6	ALBATROSS	A Learning Based Transportation Oriented Simulation System	2000	Activity pattern generation	Aspatial but includes spatial variables	Activity pattern (choice), Mode choice as transitional probability	"scheduling activities is conceptualized as a process in which an individual attempts to realize particular goals, given a variety of constraints that limit the number of feasible activity patterns"	Activity pattern generation	Not publicly avaliable	Generates activity pattern for use in an activity-based microsimulation modeling system (TDM)	Towards transport policy strategies. Especially for Travel demand management oriented policies e.g. Telecommuting, ride-sharing, flexible work time and road pricing
7	PATRICIA	Predicting Activity-Travel Interdependencies with Suite of Choice-Based, Interlinked Analyzes	2002	Activity pattern generation	Aspatial but includes spatial variables	Utility-based choice models	Utility-maximisation in choice selection	Activity pattern generation	Not publicly avaliable	Generates activity pattern for use in an activity-based microsimulation modeling system (TDM)	Developed as a benchmark to assess ALBATROSS with a different theoretical basis.
8	CEMDAP	Comprehensive Econometric Microsimulator for Daily Activity-travel Patterns	2004	Activity pattern generation	Transport network	Utility-based choice models for activity pattern	"system of econometric models"	Activity pattern generation	Trial version avaliable: caee.utexas.edu /prof/bhat/ CEMDAP.htm	Generates activity pattern for use in an activity-based microsimulation modeling system (TDM)	For use in an activity-based microsimulation modeling system
9	Aurora	Aurora	2004	Short term adjustments to activity pattern	Aspatial but includes spatial variables	Activity pattern (choice)	Utility-maximisation in choice of activities	Models of adaptation and rescheduling behavior sensitive to short term adjustments	Not publicly avaliable	Numerical simulations supported the face validity of the model" For use in an activity-based microsimulation modeling system (TDM)	Model of short term adjustments for "better forecasting"
10	TASHA	Travel and Activity Scheduler for Household Agents	2005	Activity pattern generation	TAZ based	Activity pattern (choice)	"travel mode choice is inherent in the activity scheduling process"	Activity pattern generation	Not publicly avaliable	Travel demand modelling for use in a Land Use Transport Integrated simulation system ILUTE	Towards land use and transport strategies. Applied in the Greater Toronto Hamilton Area.
11	GABRIEL	Gis Activity-Based tRavel sImuLator	2006	Stated Preference Survey	Journey planner, car-based	Route choice and changes in route choice given new information	Change of plan due to change in contextual circumstances	Development of geographic information system to assist Stated Preference Survey	Not publicly avaliable	Method for Stated Preference survey	Research in questions such as "how new techology influence travel behaviour?"in the context of Advanced

											Traveller Information Systems
12	ADAPTS	Agent-based Dynamic Activity Planning and Travel Scheduling	2009	Activity pattern generation	Aspatial but includes spatial variables	Activity pattern (choice)	"activity planning events as individual discrete events", "schedules are modified over time" in connection to a simulation of a long term context	Activity pattern generation	Not publicly avaliable	Generates activity pattern for use in an activity-based microsimulation modeling system (TDM)	Towards transport policy strategies. Especially for Travel demand management oriented policies e.g. Telecommuting, ride-sharing, flexible work time and road pricing
13	DATA	Dynamic activity-travel assignment	2015	Multi-state supernetwork	Aspatial but includes spatial variables	Activity pattern (choice)	N/A	Activity travel assignment framework	Not publicly avaliable	Numerical example	Towards an "integration of activity-based modeling and dynamic traffic assignment for travel demand analysis"
14	DATA	Dynamic activity-travel assignment	2016	Multi-state supernetwork	Abstracted transport network	Activity pattern (choice)	Dynamic user equilibrium	Activity travel assignment framework	Not publicly avaliable	Numerical example	Towards an "integration of activity-based modeling and dynamic traffic assignment for travel demand analysis"
15		Connectivity of streets	2008	Quantified metric	Street network	1. Reach 2. Directional distance	1. Street density and potential for pedestrian movements. 2. Directional change and exploratory movement	Formulation of metrics with supporting arguments	Not implemented technically	Description and justification of metrics	Develop street connectivity measures as a foundation to test hypothesis
16	UNA	Urban Network analysis toolbox	2012	Set of tools for analysis	Road and street network	Requires interpretation	Graph theory-based measures relationship to people requires interpretations	Provide means to calculate analytical measure for interpretation	Built as an extension (plugin) for use in Rhino Grasshopper and ESRI ArcGIS	From designed/generated street network to spatial metrics.	Design of urban developments including road and street networks.

17		DeCodingSpaces toolbox	2017	Set of tools for analysis	Road and street network	Requires interpretation	Graph theory-based measures relationship to people requires interpretations	Provide means to calculate analytical measure for interpretation	Built as an extension (plugin) for use in Rhino Grasshopper	From designed/generated street network to spatial metrics.	Design of urban developments including road and street networks.
18		Reach analysis toolkit	2017	Set of tools for analysis	Street network	Reach connectivity	based on Connectivity of streets 2008	Provide means to calculate analytical measure for interpretation	Built as an extension (plugin) for use in Rhino Grasshopper	From designed/generated street network to spatial metrics.	Design of urban developments including road and street networks.
19		UrbanMetrics	2017	Set of TOD-based evaluative measure as fitness function for optimising urban layouts	Street network	Proximity to amenities and facilities	Assumes Transit-oriented development principles	Principle - index - tool Operationalisation of six indice 1. Physical proximitiy 2. Topological proximity 3. Amenities variety 4. Amenities recurrence 5. Mixed-use index 6. Spacematrix density indicator	Built as an extension (plugin) for use in Rhino Grasshopper	Calculated indices based on given spatial and locational data	Develop indices as fitness function to a spatial optimisation algorithm
20		Urbano	2018	Connects designed street network and "Walkscore"	Street network	One form of walkability as a qualitative index	"Walkscore" was not developed in a scholary context, however, there are studies that supports Walkscore "as a reliable and valid measure of estimating access to walkable amenities"	Provide means to calculate evaluative indices in spatial contexts	Built as an extension (plugin) for use in Rhino Grasshopper	From designed/generated street network to spatial metrics.	Supports the design of walkable neighbourhoods
21		Reach analysis algorithms	2019	Set of tools for analysis	Street network	Reach	based on Connectivity of streets 2008	Development in the onotological aspect in terms of graph structure towards calculation of analytical measure	pseduo-code and algorithmic formulation described	Alogrithms to calculate spatial metrics	Development of the graph representation (computer ontology) as "foundation for more advanced graph-based street network analysis"

22	MTM	Mobility Topography Model	2017	Map of probable mode choice and test future siutations e.g. A new travel mode	Transport network	Probable mode choice	Probability of mode choice based on a utility function includes characteristics of transport network	A variation of traditional four step model to estimate the spatial distrubition of the most probable travel mode.	Built as an extension (plugin) for use in Rhino Grasshopper	Visualisation of the sptial distrubution of the most probable travel mode	Understanding possible impact on modal split on the introduction of a new travel mode visualised in a spatial map
23	MASTIC	Model of Action Space in Time Intervals and Clusters	2002	space-time indicator of accessibility and influence of spatial design (distrubution) on the choice	Locations of oppotunities, opening hours	Activity programme	"Spatial configurations can facilitate behaviour or, alternatively, hinder it", Action space as a person-based accessibility indicator	To understand possible travel mode choice given locations of activity participation and transport system	MASTIC has been developed in the 1990s. This study is an example of its application in context.	Potential action space for household location. Applied in Zoetermeer as a case study.	To understand travel mode choice within a framework of space-time oppotunities.
24		Space-time accessibility measures: A geocomputational algorithm	2003		Locations of oppotunities, opening hours	Space-time prism and spatial constraints - Potential Path Area	Space-time prism (STP) and potential path area (PPA)(from classical time geography)	A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration			
25		People-based joint accessibility	2008	Accessiblity measure towards analysis of joint accessiblity and their potential space of interaction	Locations of oppotunities, opening hours	Space-time prism and spatial constraints	Space-time prism (STP) (from classical time geography) and constraint-based approach. Intersection space as a prequisite of physical interactions between two individuals	Development to compute the spatial analytical Potential Interaction Area between two person in a hybrid CAD/GIS system	explored the possibility of a hybrid CAD/GIS system Autodesk AutoCAD and Map 3D 2006. Developed using VBA	"elaborate two space–time scenarios as an illustration" of the Potential Interaction Area (PIA)	"useful for the study of interaction spaces"
26	MAMPAM	Multi-Activity Multi-Person Accessibility Measure	2009	Accessiblity measure towards analysis of joint accessiblity in an urban context	Census tracts (Zones)	Individual-household activity pattern, Time allocation		Development of an evaluative index	GIS-based, no technical details specified	An accessibility measure demonstrated as a case study in Utrecht as spatial variations.	to investigate household accessibility across zones

27	SAL	Structural Accessibility Layer (SAL)	2010	Accessibility measure towards policy design and planning (travel mode and land use spatial distrubution)	Spatial disturbution of land use, Transport network	Accessibility comparison between different modes at locations	"land use and transport system enable individuals to reach different types of opportunities"	Development of an evaluative index	Developed as an extension for use in ESRI ArcGIS	1. Diversity of activity index 2. Accessibility cluster as a comparison of travel mode	"design support tool for integrated land use and transport planning providing foresight for how specific land use and transport policies constraint travel choices of inhabitants"
28	MMUN	Multimodal urban network (MMUN)	2014	Analytical framework	Transport network	Flow (demonstrative example in Randstad city-region	Example test correlation between network flow and different types of distance measures	Development of the analytical environment - specification of entities required for different types of distance measure and metrics	PostgreSQL and PostGIS	GIS-based analytical framework	To describe the "multimodal structure of a city region".

Literature review: analytical approaches

Approaches	**Metrics of urban characteristics**	**Modelling and estimate future transport/travel activities**			**Accessibility-based**		
					Location-based	**Person-based**	
Focus	**Patterns of transport/travel activities** correlates to measures of urban characteristics	**Estimate the amount of transport/travel activities** given a description of physical space and transport infrastructure			**The constraints in physical movements** given the physical space and transport infrastructure	**The constraints in the possibilities to reach opportunities** for one or multiple daily activity programmes given the physical space and transport infrastructure	
Analytical construct	Analytical construct as metrics of urban characteristics. justification and **formulation of** "**distance measures**" beside metric distance such as topological, angular, **formulation of representation** of urban characteristics e.g. axial map, segment map statistical explanation	Analytical construct as mathematical (gravity-based) model to compute **flows** between cities/ zones from production and attraction data typically from census data	Analytical construct as model and analysis of **individual travel behaviour** **"disaggregate behavioural models"** "utility models" (based on economics) and "attitudinal models" (based on psychology) (Banister, 1994) That can be used as part of a transport/ travel demand model.	Analytical construct as model and analysis of **activity pattern** That can be used as part of a travel demand model.	Analytical construct as metrics of location-based accessibility. In addition, impedance (e.g. speed, travel time, waiting time, cost), threshold (e.g. distance or time for contours) by justified choice or choice by researcher / construct operator Cumulative opportunities, Topological, Gravity-based	Analytical construct as metrics of person-based accessibility. Measures of accessibility using metrics based on a set of feasible or possible opportunities specific to one or a set of activity programmes.	Analytical construct to find the possibilities of movement (Lenntorp, 1976) or feasible opportunities set (Golledge, 1994) **for activity programmes that requires the traversal of physical space to be performed** within a period of time within the facilitates and constraints of the urban situation. Labelled under "activity-based approaches" (Banister, 1994) and "constraint-based" under "activity-based approaches" (Timmermans)

Example	Space syntax	Transport models	Behavioural models	Activity-based models	Location-based accessibility measures	Space-Time based accessibility measures	Space-Time model-based approaches
Presumptions required for scenario analysis	Hiller et al (1993) **theory of natural movement** suggests the layout configuration is the primary generator of movement patterns	Four types of **spatial interaction**: 1. spatial physics 2. statistical mechanics 3. aspatial information processing 4. spatial information processing (A. S. Fotheringham, C. Brundson, 2000, p. 215)	Behavioural presumptions e.g. **utility maximisation**	Presumptions of **derived demand** – travel activities have a destination that is differ from origin	**Physical presumptions** (distance between physical space or time to traverse physical space) Gravity-base **Presumptions of "attractiveness**" Cumulative opportunity-based **Presumptions of threshold** distance or time (common in TOD related studies)	**Physical presumptions** (distance between physical space or time to traverse physical space) **Presumptions of human condition** under time geography framework (note 1) The necessary condition for physical movement **varies by individual** as well as situation (Miller, 2017b)	**Physical presumptions** (distance between physical space or time to traverse physical space) **Presumptions of human condition** under time geography framework (note 1) The necessary condition for physical movement **varies by individual** as well as situation (Miller, 2017b)
Main references	Hillier; Penn;	Willumsen; Hensher;	Ben-Akiva; McFadden	Timmermans; Miller E	Guy 1983; Handy, 1997	Miller H 1991; Kwan 1998; Neuten et al 2008;Soo et al 2009	Lenntorp 1976; Dijst 1995; Kwan, 1994; Kwan and Hong, 1998

Table. Overview of three broad approaches and main lines of relevant research

Each cell highlights elements included in approaches below (rows) but excluded in approaches to the right (columns)	**Space Syntax**	**Transport models (4SM)**	**Behavioural models**	**Activity-based models**	**Location-based accessibility measures**	**Space Time-based accessibility measures**	**Space-Time model-based approaches**
Space Syntax	X	Spatial configuration at the scale of urban fabric and space in between; does not rely on origin-destination data	Relation of spatial configuration to aggregated pattern of movement	Relation of spatial configuration to aggregated pattern of movement.	Space syntax accessibility - Specific topological formulation of both representation of space and alternative distance measures. Suitable for pedestrian and vehicle (with driver) accessibility given the theoretical justification of metrics.		
Transport models (4SM)	Spatial interaction between cities and zones; modal split; Assumptions of origin-destination pairs	X	Macro scale pattern - Quantified amount of flows and modal split	Macro scale pattern - Quantified amount of flows and modal split			
Behavioural models	Individual motivation and goal-directed behaviour	Individual motivation and goal-directed behaviour	X	Individual constraints in space and time, and in some formulations, motivation and goal-directed behaviour			
Activity-based models	Individual constraints in space and time, and in some formulations, motivation and goal-directed behaviour	Individual constraints in space and time, and in some formulations, motivation and goal-directed behaviour	Closely related, there are behavioural formulation of activity-based models.	X	See space-time accessibility	Focuses on activity pattern analysis and generation towards TDM but not an applied measure for policy purposes	Closely related, transport-related research in analysis and generation of activity patterns
Location-based accessibility measures	Space is explicitly represented in geographically; use of space is important as opportunities;	Space is explicitly represented in geographically; use of space is important as opportunities;	Space is explicitly represented in geographically	Space is explicitly represented in geographically	X	Provides objective measures associated to locations	

<table>
<tr><td></td><td>usually includes entities that at a lower spatial scale– such as the “weight” or “size” of opportunity</td><td>usually includes entities that at a lower spatial scale– such as the “weight” or “size” of opportunity</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Space-Time based accessibility measures</td><td>Person-based, constraint based

Includes all travel modes if model can be constructed for the travel mode</td><td>Person-based, constraint based</td><td>Concepts of constraints, both spatial and aspatial in terms of capability, authority and coupling</td><td>Metrics not used under activity-based approaches for modelling.</td><td rowspan="2">Similar in constraints by space and time, differ in the basis of “accessibility”. Space time approaches starts from personal/joint activity programmes

Differs by different population groups due to the way daily activities are allocated (Kwan)

The necessary condition for physical movement varies by individual as well as situation (Miller, 2017b)</td><td>X</td><td>Uses a formulation of space-time model (there are multiple) to produce a numerical value associated to a unit of space or activity, there is a focus on the interpretation of differences of interest</td></tr>
<tr><td>Space-Time model-based approaches</td><td>Multiple possibilities and person-based, constraint based;

Includes all travel modes if model can be constructed for the travel mode</td><td>Multiple possibilities and person-based</td><td>Concepts of constraints, both spatial and aspatial in terms of capability, authority and coupling constraints</td><td>Early space-time models are part of activity-based approaches commonly known as constraint-based models (Timmermans)</td><td>Process in which activity programmes are described, selected and associated to the urban environment to test for feasibility. Space-time model enables space-time measures</td><td>X</td></tr>
</table>

Table. Comparison between approaches in six main lines of relevant research