Constructing Pedestrian-Centric Street Mobility: Observation and Simulation for Design

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PhD Thesis, Intelligent Mobility Design Centre,

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During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

F. Selin Zileli, 10th January 2022

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Abstract

There are three principal components to the research presented in this thesis: a video-observation study of pedestrian behaviours and interactions with traffic, leading to the development of an agent-based digital simulation, and demonstrating the potential of this simulation for designing pedestrian-centric interventions in the streetscape. The long-term objective is to devise streetscapes that responsively adapt to the needs of pedestrians.

Since the advent of car culture in the late 1930s, the approaches to street design have prioritised efficient motorised traffic flow, restricting walking and neglecting the pedestrian point of view. In recent years, however, a growing interest in making urban spaces more pedestrian-friendly has emerged, popularising concepts such as walkability, shared space, and traffic calming. These approaches aim to promote active travel and reduce car dependency in order to mitigate congestion, pollution, accidents and other harms.

Urban studies have concentrated primarily on pedestrian-only zones and utilised spatial features as a way to reach pedestrian-friendly streets. Meanwhile, transport studies have tended to approach the street from a throughput and vehicle-oriented stance. Despite these endeavours, pedestrian-oriented approaches appear to lack systematic consideration of pedestrian behaviours as they interact with motor vehicles and street infrastructure. My PhD research differs from prior studies by focusing on these behaviours and interactions to support a pedestrian-oriented street mobility system.

The current design of streets communicates to pedestrians via its structures and signs, such as barriers, crossings, and lights, while its capacity to respond and adapt is minimal. In contrast, this thesis argues that, since the street environment is inherently dynamic, we should analyse its dynamics and design the street to be responsive. Through responsiveness, my aim is to increase the convenience of pedestrian movement whilst creating a safe experience.

This PhD asks the question 'how to design a pedestrian-centric street system that dynamically manages street mobility?'. The research takes a practice-based and reflective approach, designing agent-based simulations based on a qualitative observational study. Designing a simulation accomplishes two things: 1) it creates a space for implementing and evaluating possible design interventions, and 2) it prompts new insights into the behavioural processes of pedestrians. My research has followed an iterative cycle in line with second-order cybernetics:

in two feedback loops, the first study informed the second study while the second informed the first.

The video observation of street behaviours particularly explored pedestrian decision and interaction processes, identifying pedestrians' own observational strategies and their varying levels of risk-taking. These aspects are reflected in the simulation.

The first chapter introduces the pedestrian issues on the street and sets out the key concepts in pedestrian-centric street design. The second chapter examines the literature and existing practice that addresses pedestrian and vehicle interactions on the street. Chapter three sets out the theoretical framework and the following chapter describes the methodology. The three subsequent chapters present the following studies: (1) understanding the context by conducting qualitative video observation in a real street environment to observe and document the relations between streets, pedestrians and vehicles; (2) creating an artificial pedestrian society for simulation purposes, using agent-based modelling, both to refine the understanding developed through video analysis and to create a platform for experimentation; (3) design and implementation of prototype responsive interventions within the simulation, focusing on localised changes in the environment to empower pedestrians. The last chapter reflects on these projects by discussing the research contributions in terms of methods, techniques, and practices. The methodological innovation includes combining qualitative and computational tools as well as the use of simulation and video analysis in an iterative and reflexive cycle. Theoretical contributions include evaluating streets through pedestrian dynamics, creating a taxonomy of existing pedestrian interventions according to their spatial and temporal impacts, and rethinking the street as a responsive environment. The practical component advances the technical state of the art by expanding the capabilities of pedestrian agents when negotiating with vehicles and making crossing decisions and demonstrates the potential for designing novel interventions in the streetscape, including those that respond to pedestrian behaviour. The last chapter, also, emphasises the role of reflective design practice and the place of simulation within it.

Keywords: Responsive Interventions, Street, Pedestrian, Interaction, Video Observation, Modelling.

Publications

Wu, J., Johnson, S., Hesseldahl, K., Quinlan, D., Zileli, S., Harrow, P.D., 2018. Defining Ritualistic Driver and Passenger Behaviour to Inform In-Vehicle Experiences, in: Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, AutomotiveUI '18. Association for Computing Machinery, New York, NY, USA, pp. 72–76.

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Zileli, S., Wu, J., Diels, C., Davis, S.B., 2021. Creating Artificial Societies through Interaction Analysis: Translating Qualitative Observational Study into Agent-Based Modelling. Presented at the ALIFE 2021: The 2021 Conference on Artificial Life, MIT Press.

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Glossary

The explanations that follow are intended to introduce the words that are particularly important for this thesis. The terms are associated with various aspects of the thesis, such as the literature review, theoretical framework, qualitative observations, and agent-based modelling. Most of the terms are defined more fully through in-depth discussion later in the thesis.

Adaptation: The term is used to describe two types of adaptation. One refers to pedestrian's adaptive behaviours to the environment (only in Chapter 6). The other refers to the street's proposed ability to adapt to pedestrian behaviours. While the first investigates the various responses of pedestrians to changing situations, the second investigates how to create a responsive and dynamic pedestrian-centric street mobility system.

Agent: The term refers to artificial entities that have autonomy, act independently of direct influence, or are not subject to centralised control. In this thesis it refers to artificial pedestrians and vehicles.

Conflict: The term conflict also has two meanings. One defines broader conflict between pedestrians and vehicles which can be considered a conflict of interest. This conflict is explored in the Introduction and Theoretical Framework chapters when defining car-centric and pedestrian-centric thinking. The term is also used to refer to the actual conflicts that occur in the street environment between pedestrians and vehicles when both need to move through the same space. This definition of conflict is primarily used during the three practice studies.

Conflict Points: This term refers to the intersection points between the routes of pedestrians and vehicles, either formal, such as pedestrian crossings or informal, such as in between the vehicular traffic.

Convenience: This term refers to the benefit of pedestrian permeability, namely having freedom to move around the space and increased access for pedestrians.

Crossing Period: Crossing period defines the time frame used by pedestrian to cross the road or the pedestrian crossing.

Dynamic: The term refers to practices in the street that are planned to be in constant change. In the thesis, dynamic practices are principally considered as street's ability to adapt to pedestrians.

Permeability: This term, in this research, is used to refer the extent to which the street intervention permits or limits pedestrian's movement. Further discussion about the term can be found in Chapter 2.

Responsive: This term is used for dynamic adaptations that facilitate the goal of the system. Further description of responsiveness can be found in Theoretical Framework.

Situational or Contextual: These terms are used to define the pedestrian's relation with changing conditions including vehicles, other pedestrians, and infrastructure.

Static: The term refers to the physical and spatial aspects of the environment that are not planned to change, in most of the thesis, except in Chapter 6. In that chapter, where the simulation is explained, the word static refers to variables that do not change.

Street Mobility: This term refers to the mobility options that are available in the street level. These include mainly vehicular mobility, pedestrians, and other micro mobility options.

Chapter 1 Introduction

For most of the last century, urban street space has been considered through a car-centred perspective, resulting in an imbalanced competition between people and vehicles (European Commission and Directorate-General for Environment, 2004; Fruin, 1971, p.1; Nello-Deakin, 2019). This car-centric approach to urban space had damaging consequences for human health, climate change and cities as liveable spaces (Nieuwenhuijsen, 2020). Recent technological advancements, such as higher levels of autonomy in the automotive industry, as well as the introduction of IoT sensors and Big Data to the cityscape, are viewed as key catalysts for street space (Carter et al., 2020; Duarte and Ratti, 2018). While one of the aims of autonomous mobility is to reduce traffic accidents by taking the driver out of the loop (Kim et al., 2019), IoT sensors and Big Data are viewed as tools to obtain data sets to improve city services (Carter et al., 2020). Essentially, I believe that these implementations offer an opportunity to reconsider streets to ensure pedestrian-centred planning. Therefore, in this PhD, I explore the question of how to design pedestrian-centric street mobility. This is explored through three principal studies which are: a qualitative observational study of pedestrian behaviours and interactions, leading to the development of a simulation tool, and the use of this tool in order to illustrate an example of dynamic pedestrian-centric intervention. With the research question in mind, the goal is to analyse and understand pedestrian behaviours in order to design dynamic and pedestrian-centric design interventions that in the long term devise streetscapes and adapt to the needs of pedestrians.

By "pedestrian'' I mean all those individuals who move through the street on foot (or using mobility aids such as wheelchairs) negotiating with other mobility types. Streets enable different types of mobility modes ranging from active mobility such as walking and cycling to public and private transport. The main concern of this thesis is the pedestrian's mobility activities, interactions, and behaviours, considering streets as a mobility facilitator.

Before discussing this research, it is helpful to give some background about the street environment, outline the issues on the street and set out the key concepts. In the following section, I provide an overview of the background on the car-centric approach to cities and its consequences. Then, I will focus on the issues that concern pedestrians and how they have been addressed by others. In the following section, I will evaluate the current state of the literature to state the gap and contribution of this research. Later on, I will outline the research focus, and I will conclude the chapter by briefly describing the methodology, findings and layout of the thesis.

Background: From Car-Centric towards Pedestrian-Centric Design

> 'Modernist urban landscapes were built to facilitate automobility and to discourage other forms of human movement. . . .[Movement between] private worlds is through dead public spaces by car' - Freund and Martin, 1993, p.119.

Since the introduction of automobiles into the streets, several proposals have sought to resolve the conflict between the ever-increasing number of cars and their large-scale requirements (roads, power supplies, signs, and other novel objects) and the much finer grain and slower speeds of active mobility. For much of the 20th century, streets were designed to ensure smooth motorised traffic flow and not foster the other functions of streets, such as accommodating pedestrian mobility (Shelton, 2011).

In the 20th century during the interwar period, urban planning proposals aimed to maintain the good aspects of the city while leveraging the possibilities of the automobile: Ludwig Hilberseimer's High-Rise City of 1924 (Figure 1.1), Hugh Ferriss's The Metropolis of Tomorrow of 1929 (Figure 1.2), Le Corbusier's La Ville Radieuse of 1930 (Figure 1.3), and Norman Bel Geddes's Futurama of 1939 (Figure 1.4) to name a few. Even though they were speculative interventions in the city's morphology, these investigations were some of the first attempts to deal with questions we are still grappling with today: how do we define the relationship between vehicles, environment, and people?

While the car was viewed positively, energetically campaigned and fought for through these proposals, they also started to demonstrate the constraints it brought to the environment and its users. Cars are viewed as a means for exercising the individual's right to move freely. This movement dependency of users disrupted the taskscape of other users who are viewed as barriers to fast traffic (Urry, 2004).

The most obvious result of this conflict between the car users and other road users such as pedestrians is the road crashes that are a result of speed increase (Tranter, 2010). This increase led to segregations between pedestrians and vehicles in order to protect pedestrians whilst creating impractical, inconvenient or unpleasant pedestrian routes to follow (Stipancic et al., 2020). Segregation of different modes caused considerable devotion of space to vehicles as they were more space-intensive than other modes (Gössling, 2020). However, increasing the road space for vehicles did not relieve the problem of congestion (Vuchic, 2017), as the wide adoption of vehicles continued.

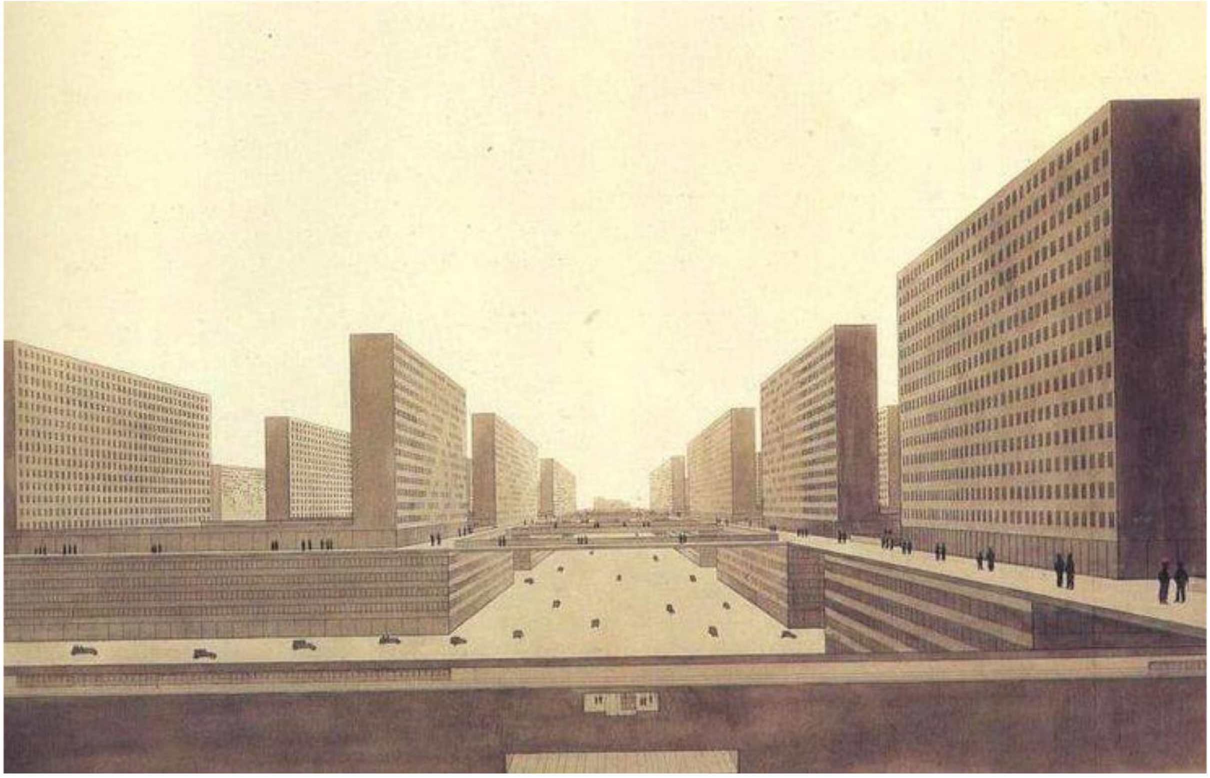


Figure 1.1. The High-Rise City, L. Hilberseimer, 1924.

Figure 1.2. Walkways overlooking the motorised traffic. Source: The Metropolis of Tomorrow, H. Ferris, 1929.

Figure 1.3. La Ville Radieuse (The City Radiant with Joy), Le Corbusier, 1930.

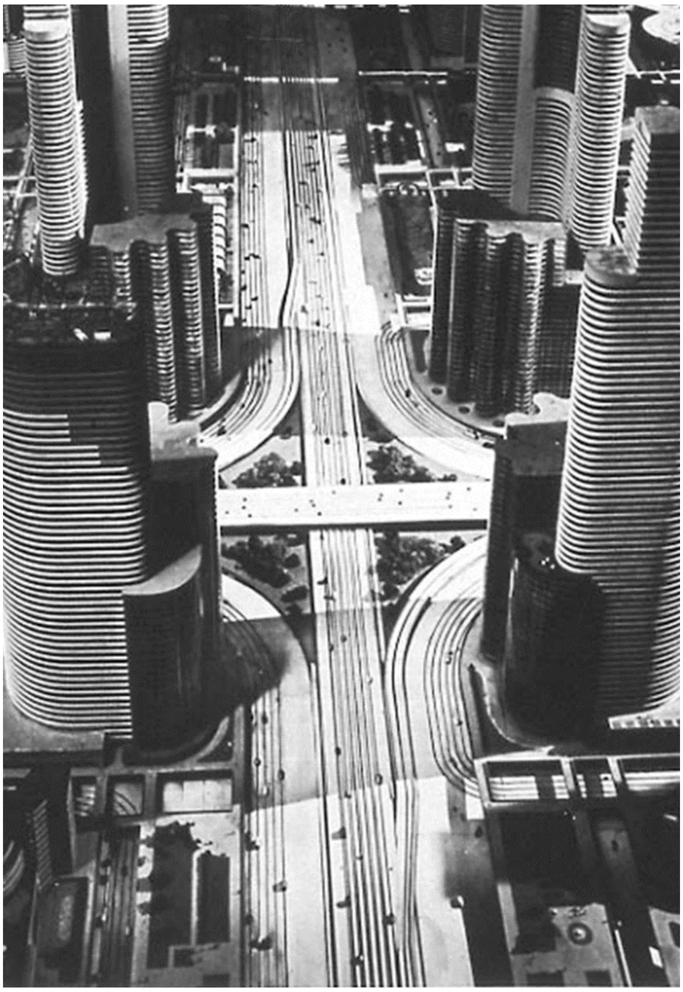


Figure 1.4. Aerial view of Street Intersections in the Futurama Exhibition. N.B. Geddes, 1939.

Figure 1.5. A Frame from 'Playtime' Movie, Jacques Tati (1967).

This excessive use of automobiles with congestion brought inefficiencies in social, health and environmental externalities such as decreased quality of life (Hart and Parkhurst, 2011), health problems (Tranter, 2010), decreased air quality (Slovic et al., 2016) and increased greenhouse gas emissions (Nurhadi et al., 2017).

The concerns over increased use of vehicles and car-centric planning revolve around a set of interconnected subjects. The reduced safety of pedestrians and cyclists increased the dependency on vehicles (Hamilton-Baillie, 2008). Increase in vehicle use also meant reduced activity and mobility for people which increased the obesity levels. For example, according to Frank et al. (2004) each additional hour spent in a car raises the chance of obesity by 6%, whereas walking each additional kilometre per day reduces the likelihood of obesity by 4.8%. This growth in car usage also affected the journey times creating the ongoing problem of congestion. The growing demand for travelling with a vehicle also created problems such as noise and pollution (Cullinane, 1992) through producing increased levels of CO_2 emission.

With progressive urbanisation, one of the most prominent global trends in today's world, it is expected that by 2050 68% of the world's population will live in cities ([UN DESA] The Population Division of the United Nations Department of Economic and Social Affairs, 2018). According to the most recent projections, London's population has grown to 9.4 million individuals (Worldpopulationreview.com, 2021). Transport for London (2018) expects this number to rise to 10.8 million individuals in the following years, which means there will be millions of additional journeys every day. The increase in the number of journeys would exacerbate the problems of increasing congestion, pollution, and ill health. Promoting active mobility, such as walking and cycling combined with public transportation, is one way to tackle these problems. The Mayor of London's transport strategy also supports this stance by aiming to make 80 percent of trips through walking, cycling, or using public transport (Mayor of London and Transport for London, 2021).

In this research, I chose to focus on pedestrians because, although it is one of the most natural and simple ways of getting from one location to another, walking is rarely considered explicitly as a mode of transport. It is regarded as a complementary mode of transport linked with other modes of mobilities such as public transportation, cycling or private vehicles. Walking information (such as start, end locations or durations of trips) is frequently overlooked since it is challenging to collect: the individual always may walk to any location ad hoc, so that trips are harder to define, and capture data for, than those that are vehicle-based (Wigan, 1995). This ambiguity in the definition of trips has led to either ignoring the pedestrian travel choices or estimations based on incomplete information. Furthermore, since walking can be performed in any area without needing a specific infrastructure, pedestrian's needs and demands in the context of mobility are neglected. As a result, the design of roads has prioritised the flow of vehicular traffic, which needs infrastructure and is designed to restrict pedestrian movement.

With the focus given to motor vehicles, walking, an inherently safe mode of transport, became dangerous. Reported road casualties Great Britain annual report of 2019 shows that pedestrians accounted for 27 per cent of fatalities, the second highest rate amongst the road users (Department for Transport, 2020). The highest percentage of contributing factors which led to accidents were shown as driver or rider failing to look properly by 46%, driver or rider failing to judge other person's path or speed by 23 per cent, driver or rider was careless, reckless or in a hurry by 18% (Department for Transport, 2020). The other factors are poor turn or manoeuvre (17%), loss of control (13%), pedestrians failing to look properly (9%), slippery road due to weather (8%), travelling too fast for conditions (7%), exceeding the speed limit (5%) and sudden braking (7%). The majority of contributing factors to collisions presented by the Department for Transport (2020) involve vehicles. Whilst being a pedestrian is unsafe because of the higher possibility of being killed or injured by vehicles, pedestrians pose minimal risk to other road users. This vulnerability stems from car-centric thinking, which exposes pedestrians. A number of studies, such as Iravani and Rao (2020), suggest that the number of fatal accidents reduces when the street design is centred around pedestrians rather than cars.

Concepts in Literature that Addresses Pedestrians

There is a growing body of research and interest in creating pedestrian-centric urban spaces. An increasing number of concepts are developed and used in the literature. I will be explaining these concepts in this section. First of them is *walkability*, a concept introduced in the post-modernist planning era to increase the attention given to non-vehicular transportation. There have been several proposals that align with the principle of walkability. Some of the examples are the healthy streets approach in the UK (Transport for London, 2017), the complete streets approach in the USA (LaPlante and McCann, 2008), the greater streets approach in Canada (Ryerson City Building Institute, 2018). Whilst these concepts require a collaborative approach between urban planners and transport planners, they originated from the urban planning field. For this reason, I also explored which concepts are explored in transportation planning. Further, I looked into the current trends that address some of the problems I mentioned in the previous section.

Walkability

Walkability, which originated in response to the negative consequences of the car-centric approach (Rišová, 2020), is one of the concepts that underpin the design of pedestrian-centred streets. Walkability is a widely-used term that refers to several different kinds of phenomena (Forsyth, 2015). Forsyth (2015) classified walkability research in three main subjects which are (1) walkability to enhance environmental conditions (through traversability, compactness, safety, or being physically enticing), (2) walkability to reach certain outcomes such as liveable spaces, increasing sustainable transportation, or increasing physical activity and (3) as a framework to design through its various measurable dimensions or as a tool for providing holistic solutions to urban challenges. According to her, associated with these various approaches and outcomes the walkable environment can have different outcomes that may not necessarily support desired features that are envisaged when using another walkability definition.

Similarly, Zuniga-Teran et al. (2017) emphasise two topics in walkability studies: mobility and recreation. In one, walkability is viewed as a component of urban mobility that is primarily addressed by the urban planning field through morphological features such as connectivity (e.g. Dovey and Pafka, 2020) in connection with other disciplines like transportation studies (e.g. Park et al., 2014), urban geography (e.g. Middleton, 2010; Waitt et al., 2019) and politics (e.g. Henderson, 2009). The other approach is primarily concerned with walkability as a means of encouraging physical activity, recreation, social interaction, and reducing obesity (e.g. Fenton, 2005; Sallis et al., 2010).

When designing walkable spaces, urban planners take several principles (see Figure 1.6) into consideration. Researchers use these walkability principles in order to assess how streets are connected, their links with other modes of transportation, their accessibility and safety, their land usage patterns, the quality of the path, and the context of the environment (Southworth, 2005). Forsyth and Southworth (2008) summarised these principles as proximity, barrier-free, safe, having a lot of pedestrian infrastructure, and upscale, respectively. The first principle, proximity, is defined as being close to a particular destination. This principle is particularly measured through cost-benefit calculations, such as whether driving to a specific destination is worthwhile. The second principle describes an environment with no significant barriers, with connections and that can be accessed by various pedestrian groups (elderly, disabled, children etc.). The third principle analyses environmental safety by examining perceived crime or perceived traffic. The fourth principle examines the environment based on its ability to support pedestrians with visible displays and pedestrian-centred infrastructures such as pavements, crossings and street furniture. The last principle evaluates the environment's appeal to the upper-middle class lifestyle, which primarily includes the area's land usage and architectural scope.

In the literature, researchers measured walkability through population density, land use, street layout, pavement presence, the network of roads, and pavements. The researchers choose different tools to analyse various aspects of walkability, such as GIS (e.g. Telega et al., 2021) and Space Syntax for land use, density, pavement presence as elements of connectivity (e.g. Baran et al., 2008; Scorza et al., 2021), a survey-based respondent mapping tool to measure attractiveness of the environment (e.g. Adkins et al., 2012) and Walk Score® to measure proximity to preselected destinations, street connectivity, and density (Hall and Ram, 2018). The term *liveability* can summarise the contribution of walkable environments. Fenton (2005) gives an example of the concept by emphasising the link between building more physically active communities and the increased liveability of a city. The walkability concept was found particularly useful in creating economically active communities through mixed land use. Goetzke and Andrade (2010) illustrate this point by analysing the effect of walkability through economic modelling tools.

In one of the critiques of walkability, Lo (2009) highlights a tendency to emphasise physical features and interventions in the literature and a lack of multi-disciplinary and research-based metrics. This critique becomes more evident in micro-level studies such as street scale, where most of the research focuses on physical changes to improve the environment by adding parking arrangements, street pavement and pedestrian crossing. Such approaches, however, have not treated the relationship between local walkability and other modes of transportation, such as cars, in much detail (Shields et al., 2021). Another interesting point is that even though walkability research consists of dynamic features such as density, the temporal aspect of these parameters is not observed in the literature.

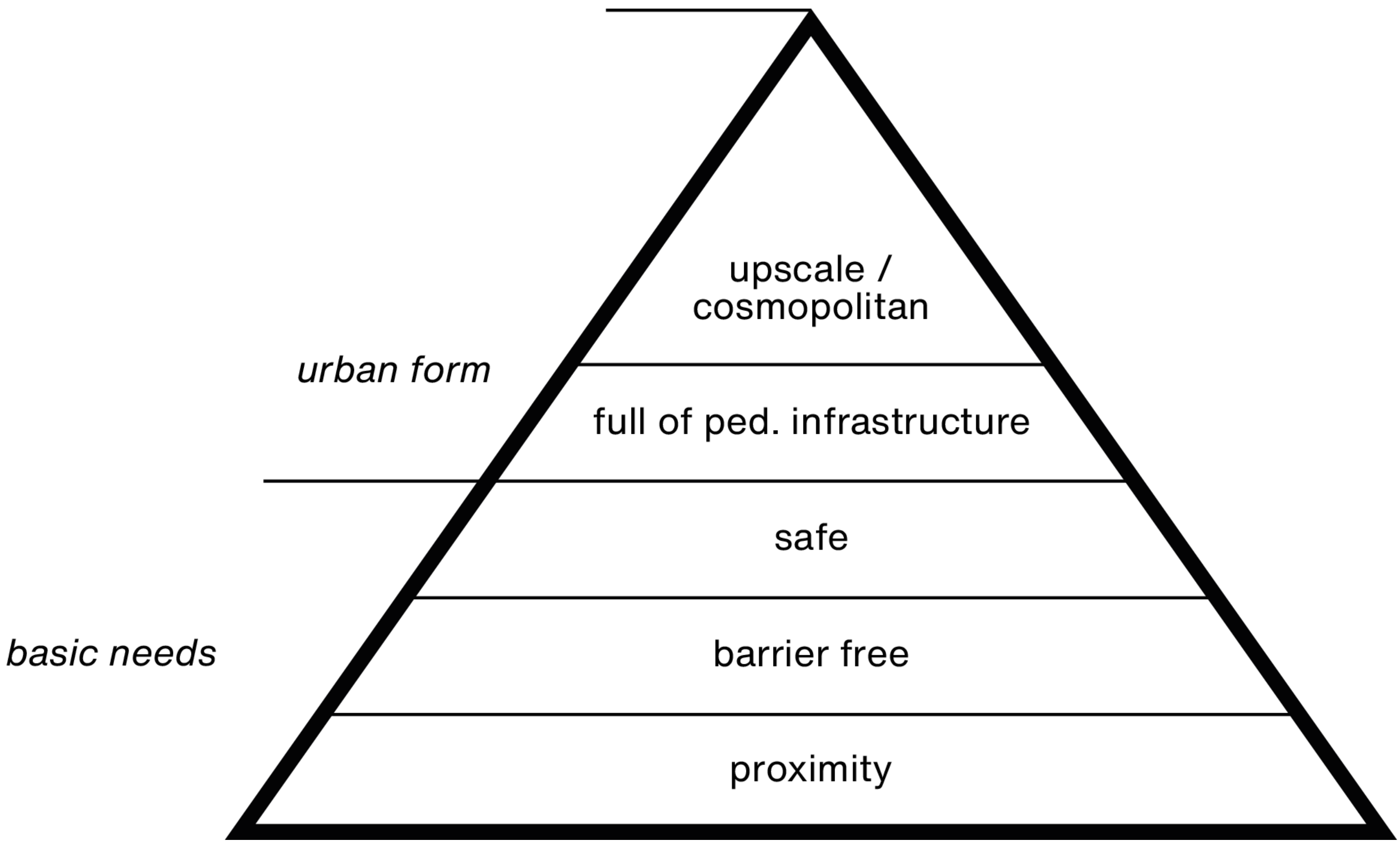


Figure 1.6. "Hierarchy of Walkability Needs" from Forsyth and Southworth (2008).

Pedestrian-centric Street Proposals

In parallel to walkability, a number of proposals sought to explore pedestrian-centric street properties in different parts of the world (e.g. Toronto Greater Street by Ryerson City Building Institute (2018); Complete Streets by the United States Department of Transport (LaPlante and McCann, 2008)). An example of this is the studies carried out by Transport for London (2020), which presented the Healthy Street Approach to increase travel-related active mobility. This strategy focuses on building pleasant, safe, and appealing streets where noise, air pollution, accessibility, and lack of seating and shelter are not discouraging for people. The approach employs ten indicators (Figure 1.7): different types of pedestrians, ease of crossing the street, providing a shelter, places to stop and rest, not too noisy, a street where people prefer active mobility or public transport, feeling of safety, attractions, comfortable and relaxed environment, clean air (Transport for London, 2017).

Some of the proposed measures included in this plan are to allocate more space for pedestrians and cyclists, giving priority to public transport, installing pedestrian crossings where people want to cross, implementing lighting and other infrastructure, planting trees and increasing the greenery, maintaining pavements, streets and public space, reducing speed limits and narrowing carriageways. The most recent instance of this plan is the green man authority, in which traffic signals constantly display a green signal for pedestrians until traffic is detected. When there are vehicles, pedestrians are stopped on a red signal and cars are given the green light to proceed (Rogers et al., 2019).

One of the critics of these kinds of proposals is the segregationist design approach with the aim of creating safety. Tight et al. (2004) criticises these types of segregationist approach by arguing that they impair pedestrian comfort in order to reduce the potential hazards or dangers. Pedestrian overpasses and underpasses are extreme instances of this method, but the same idea also underpins the usage of guardrails and light-controlled crossings (Tight et al., 2004). In contrast, the Healthy Streets proposal takes a different approach by taking into account the route choice of pedestrians when placing the crossings during the planning stage.

Figure 1.7. Healthy Streets Indicators. Source: Lucy Saunders, Healthy Streets for London Report by Transport for London.

Pedestrianisation

Pedestrianisation is a popular strategy for separating pedestrians from vehicular traffic in order to attract them to safe, comfortable and interesting environments (Ghahramanpouri et al., 2012; Robertson, 1993). The Oxford Dictionary describes *pedestrianisation* as "the process of making a street or part of town into an area that is only for people who are walking, not for vehicles" (Oxford, 2021). Therefore, pedestrianisation is to convert an area in order to fit the pedestrians' use by excluding elements related to vehicles (Soni and Soni, 2016). Car-free space or city, or pedestrian zones, are other popular terms used to describe the same concept.

The focus on pedestrians rather than vehicular use is designed through accommodating and serving a number of stationary and non-stationary events for pedestrians (Ghahramanpouri et al., 2012). Whilst stationary events can include sitting, standing, lingering, non-stationary events are activities such as walking and shopping. Pedestrianisation can be achieved through limiting traffic (Ghahramanpouri et al., 2012), increasing convenience and attractiveness for non-motorised mobility, improving pedestrian infrastructure (Ortegon-Sanchez et al., 2017) and facilitating movement for non-car users (Melia, 2010). Therefore, designing lifestyle-related aspects of streets such as public spaces, passengers' mobility, buildings, and delivery services concentrates on serving urban life and being people-centric (Ortegon-Sanchez et al., 2017).

The aim of providing such a concept is to promote sustainable transport, improve quality of life, reduce car-dependency (Ortegon-Sanchez et al., 2017) and hence decrease congestion, pollution and noise (Soni and Soni, 2016). By providing spaces for social interactions and commercial exchanges, it also recovers space for pedestrian and non-traffic activities. Therefore, pedestrianisation is often used to improve the environment in downtown areas for increasing pedestrian circulation, air quality, streetscape quality (Parkhurst, 2003), environmental and commercial aspects of the space (Whelan, 1994).

Wooller et al. (2012) outline some of the benefits of pedestrianisation, including greater physical activity levels, reduced car dependency, and improved economic activity in the pedestrianised area. Parkhurst's (2003) findings suggest reduced vehicle activity around the area and an increase in pedestrians at the intervention site in Oxford. According to Keserü et al. (2016), these changes in modal share of trips are projected to enhance air quality, health, and congestion, as well as reduce noise pollution. However, they also mentioned that observing these impacts of pedestrianisation schemes is challenging as changes in areas such as air quality can be attributed to other factors such as improved automotive technologies. More broadly in studies of pedestrianisation, it may be difficult to monitor different results to capture changes before and after pedestrianisation. These results most often focus on volumes such as volume of traffic or volume of pedestrians (e.g. Parkhurst, 2003; Soni and Soni, 2016). However without a regular travel behaviour survey it is very challenging to assess whether pedestrianisation schemes had a direct impact on the area (Keserü et al., 2016).

One of the immediate impacts of pedestrianisation in the surrounding environment can be traffic displacement as a result of restricted motor vehicle entrance to the pedestrianised area (Keserü et al., 2016). Another impact mentioned by Keserü et al. (2016) is decreased availability of parking. The increased pedestrian interest also can lead to higher rents in the area (Whelan, 1994) which can affect the local businesses. In contrast, Soni and Soni (2016) argues that more pedestrian traffic can also mean more potential customers for businesses; therefore it can bring more economic benefits.

Shared Spaces

Shared space is interpreted differently by various researchers. For some, such as Hass-Klau (1992, pp.237-238) it refers to traffic calming strategies, while for others, such as Bendixson (1977), it refers to residential configurations (Karndacharuk et al., 2014). According to the Department for Transport (2011, p.6), shared space is "a street or place designed to improve pedestrian movement and comfort by reducing the dominance of motor vehicles and enabling all users to share the space rather than follow the clearly defined rules implied by more conventional designs". The idea of shared space is generally attributed to Dutch traffic engineer Hans Monderman (Hamilton-Baillie, 2008; Karndacharuk et al., 2014; Methorst et al., 2007). He applied the concept of shared space as an alternative method of organising human activities in the street (Methorst et al., 2007). The concept was founded on the perceived risk that requires road users to be more aware of one another and, hence, react more cautiously. The idea of creating a less safe environment in order to increase attention is influenced by behavioural and environmental psychology (Hamilton-Baillie, 2008), mainly from the model of risk compensation (or risk homeostasis), a phenomenon shared between Peltzman (1975) and Wilde (1998), often attributed to Adams (2012). This notion states that uncertainty in an environment might diminish an individual’s tendency to take risks, resulting in them behaving more cautiously (Karndacharuk et al., 2014).

Shared space suggests reducing segregation between modes of mobility by utilising a sharing space strategy based on informal social rules and negotiation (Hamilton-Baillie, 2008). This approach encourages integrating slower and smaller non-motorised mobility users with faster and larger motorised mobility without evident segregation between them to develop a sense of place and facilitate multiple functions (Karndacharuk et al., 2014) such as accessibility, movement and liveability.

These functions are achieved by creating uncertainty to encourage cooperative and sharing behaviours between users. Uncertainty is used to achieve slower and more cautious drivers, more engagement with the surrounding environment (Karndacharuk et al., 2014), priority to human interactions, socially conscious behaviours (Methorst et al., 2007). Shared street principles promote informal interactions and mutual considerations rather than using regulatory elements such as barriers (Hamilton-Baillie, 2008). Some commonly used methods to create shared space include removing some rules, traffic lights, signs, and other traffic engineering elements (Methorst et al., 2007) to provide informal cross-flows of pedestrians and integrating the street design with local characteristics (Hamilton-Baillie, 2008).

Shared space aims to reduce the dominance of motor vehicles by promoting walking and cycling activity by using road space as a place, movement and access purposes (Karndacharuk et al., 2014). By referring to the road as a space for people rather than only traffic space, it aims to encourage people to occupy the centre stage (Methorst et al., 2007) and nurture the idea of creating a sense of place (Karndacharuk et al., 2014). According to Karndacharuk et al. (2014), this combination of the road as a movement, place and access space aims to shift the demand and expectations away from motorised traffic towards non-motorised travel and create safer mobility for all users. The shift in demand is expected to result in de-cluttered streets (Karndacharuk et al., 2014) with a coherent public space that reduces space usage for traffic and increases freedom of movement (Hamilton-Baillie, 2008).

Whilst it is argued that the shared space approach is a way to achieve these aims, it is challenging to monitor the actual success, as reduced car usage or increased traffic congestion can relate to several other factors (Keserü et al., 2016). For example, increased vehicle adoption and traffic can be due to increased income and car ownership, or increased non-motorised mobility use can depend on overestimating the car users or not considering non-car users. In terms of perception, however, Ruiz-Apilánez et al. (2017) show that pedestrian users perceived shared space as more comfortable than conventionally planned streets. They emphasise a compelling point on adopting a shared space approach by mentioning the importance of street layout as a whole rather than the individual "elements of shared space". They state that street and urban space design should consider more than inclusion or exclusion of factors such as signs, lights, kerbs, and the focus should be on street layout and use of the street space concerning the activity in the space.

Whilst this change of approach to street design and traffic planning was adopted widely by many countries to encourage all users to occupy the space, certain aspects of shared space opened profound discussions. Notably, minimising the usage of traffic signs and conventional demarcations creates confusion and uncertainty (Ruiz-Apilánez et al., 2017). According to Imrie (2012), the promotion of disembodied understanding of the interactions between individuals, space and movement (re)produced the insecurity and uncertainty of individuals, especially in some categories such as visually impaired people. Therefore, improving the perception of safety and navigational aids for individuals in these categories (Hamilton-Baillie, 2008) needs more attention when applying the shared space concept.

Another effect of removing traffic control mechanisms from the space is the greater competing demand, resulting in more conflicts between the different types of road users (Karndacharuk et al., 2014). This point strengthens the assumption that all users have to perceive danger and react with safe behaviour, which might increase the vulnerability of non-car users (Methorst et al., 2007). According to Imrie (2012), the lack of facilitation of conflicts in the shared space extends the normalisation of motor vehicles; hence it does not decentre motorised vehicles or challenge the dominance of auto-culture. Therefore, creating conflicting and dangerous situations and assigning the responsibility for dealing with such situations to the most vulnerable parties might be another aspect of the shared space concept that needs to be addressed.

Transportation Field Approaches to Pedestrians

Transportation Studies uses various concepts, such as traffic calming and pedestrian level of service approaches. This section will talk through these examples and then explore the transport policies implemented in the United Kingdom.

Traffic Calming is one of the transport strategies that aim to achieve an acceptable safe speed, reducing the volume of motorised traffic by providing safe and attractive facilities for alternative transport modes such as cycling and walking (van Schagen, 2003). Traffic calming schemes include installations to better manage the road vehicles such as speed bumps. There is a considerable amount of research that explores the measures, effects and performance of traffic calming, especially in Europe (Distefano and Leonardi, 2019). These strategies are further explained in the literature review chapter (Chapter 2).

Another concept from transportation studies is the level of service measurements for pedestrians, an attempt to quantify the pedestrian experience. Level of service (LOS) is a way to measure how well a walking facility is operating from a pedestrian point of view (Petritsch et al., 2006). LOS includes specific measurements which look into the built environment, flow characteristics and users' perception (Nag et al., 2019). The built environment has similar attributes as walkability, such as connectivity, street lights, obstacles, barriers, street infrastructure, land use, pavement measures. Flow characteristics look into the vehicle flow rate, speed, volume and walking speed. User's perception includes criteria such as maintenance, accessibility, satisfaction score, surface quality, commercial and residential factors, the volume of parked vehicles on the pavement, convenience, aesthetics, comfort, security, safety, presence of separation and pavement (Nag et al., 2019).

The current plans of transportation show a promise to improve streets. The future of urban policies mentions that safe spaces for walking and cycling will be abundant (Arup, 2018; Department for Transport, 2019). Interactive properties in mobility environments are increasing with the rising trends of technology through mobility on demand (e.g. Fröhlich et al., 2018), autonomous vehicles' interactions with passengers (e.g. Alpers et al., 2020) or pedestrians (e.g. Zileli et al., 2019) and IoT technologies that explore vehicle to vehicle (e.g. Mahmood, 2020), vehicle to infrastructure (e.g. Arras et al., 2019) or pedestrian to infrastructure communication (e.g. Lozano Domínguez and Mateo Sanguino, 2019). This provides a vision for accessible, affordable, equitable and connected mobility through the city. A new UK highway code is another example that aims to alter the hierarchy of road users, giving greater emphasis to pedestrians (Department for Transport, 2021), and adopting a principle that each type of road user should defer to the needs of the users more vulnerable than themselves.

The Current Trends

This section looks at the current trends that seem to address the needs of pedestrians. This includes autonomous vehicles and smart cities and how they aim to touch on aspects related to pedestrians.

Autonomous Vehicles

Autonomous vehicles, also known as driverless cars, are extensively promoted as a technology that will significantly improve road safety and reduce risk levels by decreasing human involvement in the driving process (Endsley, 2019). In addition to safety, another advantage of autonomous vehicles is that they promote car-sharing, which reduces car ownership. Thereby, this reduction has been associated with overcoming the challenges of urbanisation such as climate change, traffic congestion and CO_2 emissions (Faisal et al., 2019). Despite the optimism around this new technology, transitions towards new systems such as autonomy are fraught with uncertainty and complexity (Babb, 2020; Riggs et al., 2020). The potential sustainability of autonomous vehicles is dependent on the adoption and travel behaviour of the potential user. Given the current travel choices and attitudes which support car-based transport, one of the concerns is that the associated negative environmental impacts of car travel will continue (Stead and Vaddadi, 2019). Behaviour change and individual awareness have been shown as a way to overcome this potential scenario (Acheampong et al., 2021). For this reason, autonomous vehicles could give an opportunity to inform the public on their mobility choices which can also be used to encourage the public to choose sustainable active mobility options such as walking.

In terms of safety, recent advancements in the fields of perception, planning and decision-making for autonomous systems have led to significant improvements in the functional capabilities of autonomous vehicles. Whilst these advancements promise the pedestrian and other road users safety, the challenges regarding guaranteed performance and safety under all driving circumstances remain (Schwarting et al., 2018). The advancements in perception, control, planning, coordination and interaction with humans play an important role to fulfil the aim of providing a safe environment for pedestrians and other road users (Schwarting et al., 2018). Whilst these challenges mainly aim to be solved through the development of algorithms, they also provide a design opportunity to explore the road and street infrastructure to mitigate these challenges. Riggs et al. (2020) suggest that the action to plan, develop, and integrate flexible urban mobility spaces in order to maintain active mobility alongside new technologies should be taken now. This urgency comes from the historical evidence of car-centric thinking and design of the streets and aims to ensure the infrastructure of the street and urban environments is ahead of vehicle technology.

Whilst autonomous vehicles might have many benefits according to how they are implemented into the street environment, mediating the interests of vehicle users, pedestrians, and other road users will play an important role since the major disruptions of autonomous vehicles will affect urban transport, use of urban space, sustainable mobility and traffic safety. Accordingly, this mediation should not solely focus on the algorithm's abilities; instead, a more decentralised approach should be adopted on the regulation of these automated vehicle systems. In this frame, the opportunity offered by autonomous vehicles on reshaping urban streets should be used to reach a future-proofed and human-centred street design. In this context, street infrastructures can play a role to repurpose and shape the street to achieve safer and more sustainable communities. With technological developments, more importance is placed on using the Internet of Things (IoT) in the urban context, and smart city approaches bring this discussion forward by discussing how the street can impact reaching desired urban mobility outcomes. The following section, Smart City Concept, will further discuss smart urban mobility and its projection on the environment.

Smart City Concept

Within the contemporary smart city debate, autonomous vehicles represent a means of achieving an ideal city plan. According to Millard-Ball (2018), autonomous vehicles have a significant potential to revolutionise both the form of cities and the dynamics of transportation systems. Similarly, Riggs et al. (2020) consider autonomous vehicles as a critical component of smart cities. As stated in the preceding section, the introduction of autonomous vehicles causes a variety of disruptions in various aspects of the street system, including urban transportation, car ownership, infrastructure design, sustainable mobility, and traffic safety. To achieve the benefits of autonomous vehicles while mitigating their potential challenges, streets and cities must be prepared through progressive planning and forward-thinking designs (Faisal et al., 2019). This step towards future cities is primarily illustrated in the literature with the smart city concept.

The technological advancements increased the popularity of smart ecosystems, in which all areas of daily life are dependent on automated systems in some way or another. These systems can be controlled, managed and accessed remotely via smart devices that are linked to the smart ecosystem of products. The smart city concept is one example of these ecosystems, springing from the goal of coordinating and controlling traditional city infrastructure using digital technology (Ahad et al., 2020). The smart devices in the city are sensors and actuators embedded in the environment that are used to collect real-time data about the environment. They contain different types of technologies such as artificial intelligence, Internet of Things (IoT) (Ahad et al., 2020), wireless sensor networks (WSN), cloud computing services, machine learning, cameras, LiDAR, virtual or augmented reality, autonomy (Law and Lynch, 2019). These technologies have a level of connectivity that allows for quick feedback and modification in decision making.

Examples of smart devices for transportation systems demonstrate a wide range of implementations since there is a dynamic and diverse selection of requirements in cities.

Installing smart technology to gather real-time data on highways is one example presented by Riggs et al. (2019) as an approach to accommodate autonomous vehicles. Another example in literature is Syzdykbayev et al. (2019) research on navigation sensors for car crash avoidance, accident avoidance and sustainable mobility. Their research illustrates the links and interactions between various types of road users and street infrastructure through navigation sensors. As demonstrated by the examples, transportation systems are increasingly becoming digitally enabled through the use of information and communication technologies.

Smart mobility is regarded as one of the most promising topics in the smart city concept due to its potential to provide significant benefits for the citizens, planners and city stakeholders (Benevolo et al., 2016). For example, one of the prevalent concepts is the Internet of Vehicles (IoV) which is a message transmission system meant to notify all vehicles in the relevant space about incidents in real-time via broadcasting. This has been used by Zhu et al. (2018) to create a scalable network management system. Another study used smart cities to develop optimised traffic management for users to reach their destination, avoiding congestion (Adart et al., 2017). As demonstrated by the examples, one of the main advantages of smart infrastructures, such as smart roads, is that the environment's perception changes from settled and static to more dynamic, situationally and contextually aware (Toh et al., 2020). This more dynamic perception proved to increase efficiency, the level of safety and decrease the level of risk by using smart devices (Bakıcı et al., 2013).

One of the critiques of smart mobility in smart cities is that most of the implementation is in the conceptual phases, and there are small numbers of fully implemented examples (Benevolo et al., 2016). Another vulnerability of smart cities is handling socio-economic, political and technical aspects (Ghosal and Halder, 2018). According to Benevolo et al. (2016), further research can benefit from analysing the produced benefits of smart mobility in the citizen's life quality and defining a set of indicators to measure the benefits.

The smart city concept certainly addresses some of the issues that autonomous vehicle research has tended to neglect, such as the potential disruptions caused by autonomous vehicles. Under the appropriate application of smart cities, smart devices may become important in presenting real-time data about human activity. The perception change coming with smart cities from a more static environment to a dynamic one is an important shift as mobility systems can benefit from a more dynamic approach to organisation, communication, and management of streets. The tools and techniques for data collection provided by the smart city concept can be especially useful for pedestrians, therefore, in developing pedestrian-oriented streets. However, how, and what is collected through the smart devices is crucially important as the system needs to consider a variety of user types (such as the ones without smartphones). Further, there is a need to explore what information would be useful to collect for this new dynamic system and how to potentially collect them. Another critical point raised in the literature is the lack of communication and information exchange between the users, infrastructure and providers (Ghosal and Halder, 2018).

Preliminary Evaluation of Literature and Research Focus

At this point I reflect on the literature discussed so far. Many of the problems we face today in cities, such as congestion, pollution, and threats to our safety, are related to car-centric thinking. The literature suggests that a pedestrian-centric approach towards streets and cities can mitigate these problems. For this reason, in this PhD, I focus on pedestrians and examine how enhancing the role of pedestrians in the streets can contribute to the challenges faced in mobility as a whole, such as safety.

As indicated above, one of the central concepts in a pedestrian-centric approach is walkability which in part aims to encourage people to walk. However, in my PhD, convincing people to be a pedestrian is not treated as a goal; instead, I aim to use pedestrians and their behaviours as a necessary tool to shape and organise street mobility and dynamics. Pedestrian-centric design in my research meant employing a bottom-up approach to investigate behaviours, relationships, interactions of pedestrians to understand how they move through the street and designing around those movements and behaviours.

Another key trend is the shift towards a more dynamic view of the street, an approach introduced with the increase in technological innovations. This dynamic approach is employed through smart devices to sense targeted human activity. The shift to thinking of the street as a changing and dynamic environment does not have to be restricted to conventional systems with sensing and informing as an afterthought. Instead, I will show how it can also be included in planning streets that the conditions and situations will change; therefore, this dynamism given by the environment should be considered, understood, and used as a tool to change the space according to the needs of the given scenario.

In this research, I aim to merge the twin trends of pedestrian-centric design and dynamic approaches to the street by asking *how to design a pedestrian centric street system that dynamically manages street mobility*. These are combined with a view to ultimately creating a system that makes responsive decisions based on real-time pedestrian data. Such a system is illustrated by an example built within the simulation model I created. The main focus of the research is not the intervention itself but the tools I built and the methods I used to enable the design and evaluation of such systems. This research question inevitably raises the question of which pedestrian data the street system would be dependent on. To explore these questions, it is also essential to describe the dynamics pedestrians have with vehicles and infrastructure.

The Research Approach

In this PhD, the street environment is considered as a dynamic setting that includes multiple and changing variables. Previous epistemologies reframed the city as a collection of artefacts that hold more morphologic references and physical structures (e.g. Lynch, 1964; Rossi, 1984; Archizoom Studio, etc). This led to an approach towards the street environment using a non-changing and static perspective. Then, urban planning figures, such as Gehl (2010), started a shift towards a greater social bias and taxonomy of the city by looking into the social elements of the city. However, this shift did not change urban space's embedded meanings and roles as solid and stationary structures.

The latest developments in technology have transformed this perspective into a new way of thinking about urban spaces such as streets. The integration of technology has brought the notion of situated information and possibilities of creating situated interactions with devices, services, and objects. The proposals for the futures of cities, major publications and policies all point towards the new perception of the city, which is formulated through the engagement with technology towards a more complex and data-driven understanding, shifting from static materiality to considering the rising role of soft infrastructures in defining the urban experience. In evolving "smart" cities, computer technologies produce a city that is able to observe and respond to its citizens.

When the concept of 'smart' comes to light, the issue of control becomes the topic of discussion. The issue of control revolves around the subject of what or who has control over the environment as a result of the widespread integration of digital networks (Al-Kodmany, 2012 - referring to the number of examples given by Shepard (2011) in his 'Sentient City'). My PhD, coming from the idea of a pedestrian-centric street environment, asks the question of what would emerge if more control of the street was given to the most vulnerable road users in the street - pedestrians. Therefore, my research question asks how to design a pedestrian-centric street mobility to empower pedestrians in the light of current and future technologies. The current technologies such as IoT, smart cities or autonomous vehicles are seen as systems that are aimed to be interactive and responsive. However, it is not yet clear how pedestrians will be positioned in these systems.

Utilising the situated information provided by the dynamics in the environment (vehicles, pedestrians, infrastructure), this research aims to construct an information ecosystem where the behaviours of pedestrians form the data input. In this research, I am interested in the possibilities of self-organisation and pedestrian control which could result from an information ecosystem that is able to provide rich, accurate and timely information. The research aims to generate a bottom-up analysis of the processes that occur in the environment, to develop an appropriate environment to test using real-world conditions; developing an intervention which is a system that can control the environment based on the information about pedestrians. The intervention aims to generate and use a type of information in the environment that was previously unavailable (e.g., the record of risk-taking behaviour occurrence). For these goals, I used three methods (1) video observation for understanding the process that occurs in the real street environment, (2) agent-based modelling simulation using Unity3D to develop an appropriate environment for testing (3) designing an example intervention that can manage the street based on the pedestrian information.

Methods

My methods are discussed fully in Chapter 4, but it will be useful to give a brief overview here. Through this PhD, I address my research questions by first investigating the dynamics of pedestrians. This exploration involved conducting video recording sessions and qualitative observations in a real-world street context, which were then analysed using interaction analysis. The analysis then informed the design of a simulation that defined the dynamics of pedestrians through coding and spatial measures. This transfer from observation to simulation sought to improve our understanding of the dynamics between pedestrians, vehicles, and infrastructure as well as to identify the nonlinear links between these entities. This identification followed a circular process that began with translating the video analysis into the simulation, then realising that more information was required to represent the process. Therefore, returning again to video analysis to identify the required pieces of information. Thus, the processes of observation and simulation informed one another, rather than following a linear sequence. Through this combination of methods, a framework similar to second-order cybernetics is employed. This helps in uncovering and overcoming the limitations of adopting either of the methods alone.

Using simulation was equally crucial for developing a test environment that represents real-world systems because testing in the real world is more expensive and challenging due, not least, to safety concerns. Therefore, this test environment is intended to be used to test the prospective dynamic intervention and provide feedback on it.

Importance and Contribution of Research

This PhD proposes that pedestrians play a vital role in the future of streets, and of cities. As pointed out by many studies, pedestrian-oriented thinking can resolve the problems of car-centric thinking such as pollution, congestion, and traffic safety. I apply this recommended approach of pedestrian-centric design and use it as a way to shape the urban mobility system. Within this, my focus is unusual: to uncover a different perspective on the topic of pedestrian-centric thinking by focusing on the dynamics in the street.

Thus far, pedestrian-centric approaches have sought to implement static and rigid strategies for the street to support and enable walking. With technological innovations, this rigidity is capable of shifting into more flexible systems such as autonomous vehicles, smart devices, and IoT, that are connected to each other at a variety of levels. In this connected system, I ask what will be the pedestrian's role and the meaning of pedestrian-centric design?

In this research, I argue that the street environment is a changing, temporal, and dynamic system that involves road users' interactions such as vehicles, pedestrians, and infrastructure. This argument shapes this research by taking a different approach to pedestrian-centric design that aims to use pedestrian dynamics as a way to understand and intervene on the street. In this context, the pedestrian's role becomes the controlling measure of the street mobility and the concern of pedestrian-centric design shifts from physical efforts on the street to systemic strategies.

The findings of this study will benefit a number of fields. The primary beneficiary is intended to be the mobility field, where I have aimed to change the role of pedestrians from an afterthought to a leading actor of the street. Through the practical element of the research, I sought to understand the process and relationships of pedestrians and identify the dependencies in the street environment by combining video analysis and simulations. This work may help to create a better understanding of pedestrian mobility in organisations who are working on safe implementation of autonomous vehicles and the transport simulation developers who would like to create more realistic, therefore, more competent simulations. Additionally, this can also make the simulations more helpful to policymakers, urban and transport planners.

Another primary beneficiary would be the design field through the practice of using human-centred design and interactive systems design, and through the theoretical and methodological part of the research using reflective practitioner theory and cybernetics. The research contribution to design practice is performed through introducing a computational technique, agent-based modelling, into the human-centred design process. Human-centred design is used to reflect the variety of individual pedestrians in the observed video in the agent-based modelling, a computational model for simulating the actions and interactions of agents. The theoretical part of the research constitutes a contribution to design by situating the process of practice in the cybernetic framework and using reflection-in-action through the development of simulation and implementation of the intervention.

The secondary benefits to other subjects, such as qualitative video analysis and pedestrian simulations, are explained in detail in the original contributions section at the end of the Discussion and Conclusions chapter.

Thesis Structure

In the next chapter, I will be exploring the literature and practical examples that address pedestrian, infrastructure and vehicle interactions on the street and create a taxonomy based on their spatial and temporal features. In Chapter Three, I set out concepts and theories I have used through the process of framing the research. In Chapter Four, I describe methods I have incorporated in practice, their reasonings, and their processes. Chapter Five investigates the first study, which is about understanding the street environment by using video recordings and qualitative analysis. The sixth chapter aims to simulate pedestrians and their interactions for creating a testing and experimenting space. These two studies also act as process-based exploration towards improving the understanding of pedestrian's dependencies, dynamics, and perception-action loops. Chapter Seven presents a responsive design intervention that introduces dynamic features into the environment by focusing on the localised changes in the environment. This chapter explores the potential effects of an environment managed through pedestrian-centric and dynamic principles and the design intervention that is introduced into the simulation. The eight chapter discusses issues on combining qualitative and computational approaches, using agent-based modelling as a design tool, and discussing the new design approach for streets. This chapter sets out the outcomes on designing a reflective tool for designers, designing for responsive streets, evaluation and limitations of the research, and the potential directions for future research. Additionally, it concludes with the practical and theoretical research contributions.

Summary

With the introduction of cars, street environments have changed towards a direction that represents and supports car-centred mobility. This change caused several problems in the short and long term, such as the safety of other road users (e.g., pedestrians), traffic congestion and pollution. The solution for these problems given by urban and transport planning researchers is to shape the street with a more pedestrian-centric mindset. There are a number of concepts that aim to create a pedestrian-centric street environment, such as walkability, pedestrian-oriented proposals of government's bodies, transportation field's approaches such as traffic calming or improving the pedestrian level of service. These concepts show a spectrum between policies and practical applications where they addressed the issues in the limitations, such as spatial restrictions, that they have given. Essentially, the question was after the literature review to what extent these concepts aimed to ease daily mobility and negotiations of pedestrians.

The current trends that arrived with technological innovations such as autonomous vehicles and smart devices for smart cities take another stance when intervening in the environment. The environment is considered from a more dynamic and changing perspective rather than a permanent, constant, or static view. The reason for this is that the street is an ever-changing and inherently dynamic environment; therefore, it should be approached as one. If it is approached as a dynamic environment, the street can be made appropriate for the needs of its users. The long-term users of the street, pedestrians, can be the main actors in this new approach to balance the needs of the road users. This can mitigate the long-term negative effects of car-centric thinking whilst also tackling its immediate effects such as accidents, of which pedestrians are the principal victims.

Chapter 2 A Spatiotemporal Typology: Understanding the Street Interventions through Temporal and Spatial Permeability Measures

This chapter aims to understand the concept of permeability and temporality in the street context and propose a conceptual framework for classifying pedestrian street interventions (e.g., raised intersections, pedestrian overpass, smart crossing) by their degree of temporal permeability. Permeability refers to the degree to which the design of urban elements permits or restricts the movement of people or vehicles in various directions. The degree of permeability is here defined via both spatial and temporal measures. Spatial measures are the aspects of interventions that enable, encourage, disable or disallow movement to certain areas through creating obstacles, directions or guidance. Temporal measures refer to the aspects of interventions related to their longevity, response time and triggers for response (i.e., driven by a clock or activated by road users). It is necessary to understand how permeability relates to pedestrian mobility and pedestrian street interventions since it allows urban and transport planners to think about the spatial and temporal aspects of the pedestrian environment and explore the potential of pedestrian street interventions. In this context, the study presents a novel way of defining and classifying permeability. Further, it develops a framework to review the permeability of interventions in terms of spatial and temporal measures. This illustrates the temporal and spatial impact of the proposed interventions on pedestrians' navigation by creating opportunities or drawbacks on the streets. It helps identify the interventions available to address dynamic and changing situations on the streets and display where the types of interventions are of limited usefulness.

Introduction

Streets are inherently temporal environments which contain static artefacts such as buildings, roads and public spaces that provide a space for movement (Gehl and Svarre, 2013, p.113). Even though they are formed through static artefacts, the streets' performance is measured through temporal activities like movement, traffic, or commerce. Streets provide routes for individuals to navigate with various 'constraints' (to quote time-space geography), affecting their movement and their relations with the environment. These constraints, along with their opposite, the encouraging measures on the street, set the ability of movement, mode of movement and time of movement. Urban and transport planners use these constraints and encouraging measures to influence the flow of pedestrians and thereby reduce or increase connectivity, tending to either discourage or promote walking.

This part of the study explores the intersection of spatial and temporal aspects of street interventions by reflecting on their effects on pedestrian movements. Through focusing on pedestrian movement, I show correlations between the degree of choices available with the interventions and the temporality of interventions. The questions I aim to address in this chapter are:

- How do street interventions affect and encourage pedestrians' movement? Do they make it safer, do they make the journey more convenient, do they offer short cuts?
- Are these interventions appropriate for changing, complex and dynamic conditions of the street? What do they offer in terms of permeability and responsiveness?

To answer these questions, I will first examine the existing pedestrian street interventions and how they have been categorized. Then, I will look more closely at the concept of permeability and classify each intervention according to the spatial and temporal aspects of its permeability.

Pedestrian Street Interventions

Interventions include implementations of simple, light-touch measures that aim to make the street more functional, desirable or safer without requiring a wholesale renovation of the space (Transport for London, 2019). Pedestrian-focused street interventions aim to change the design of the streets in order to improve the organisation of pedestrian and vehicle flows by creating a friendly and safe space for pedestrians. They have a strategic role in enhancing pedestrian flow and forming pedestrian movement across various scales of space. These interventions include but are not limited to increasing space allowance for pedestrian movement, reducing the visual and physical impact of vehicular traffic to enhance the pedestrian environment, and decreasing vehicle speed.

Facilitating movements on the street both for pedestrians and drivers requires analysing the potential conflicts and opportunities that can be expected to emerge. Specifically, the analysis on which the designs are based involves questions such as where pedestrians are crossing, are desire lines (alternative and preferred path - explained further in the subsection called *Pedestrian Behaviour and Desire Lines*) followed, where are pedestrians stopping, and whether the pedestrians are visible to the vehicles. This kind of analysis helps to make a decision on the location and type of intervention. The type of intervention can vary from, for example, applying reflective painting on the street surface to distinguish the vehicular and pedestrian space (Hampton, 2017), to providing additional traffic light time for senior citizens to cross (Dziedzic, 2019).

In this research, by pedestrian street interventions, I refer to the physical design, materials and strategies used in the street, which seek to influence pedestrians' mobility and safety. The design of street interventions is based on urban and transportation planning concepts such as traffic calming, pedestrian exposure, visibility, desire lines and pedestrian behaviours (National Association of City Transportation Officials (NACTO), 2013). In the following section, I will expand on these concepts and the type of interventions they include.

Traffic Calming Strategies

Traffic calming strategies originated with *woonerf* (residential areas) schemes in Delft, a Dutch town, in the 1970s (Schlabbach, 1997). The "Woonerf" schemes introduced structuring the street to exclude the traffic in specific areas (Schlabbach, 1997). These areas included schools, offices, recreation grounds and community centres. The aim was restricting the speed and reducing the dominance of vehicular traffic in designated streets (Harvey, 1992). This idea was followed by other northern European countries such as Denmark, Germany and other areas of the Netherlands (Schlabbach, 1997).

The traffic calming strategies, as the name implies, are fundamentally concerned with reducing the impact of motor vehicles on the streets to improve road safety. These strategies include a broad variety of initiatives to minimise vehicle speed and enhance the environments (Pérez-Acebo et al., 2020). The initiatives are structured to complement each other in order to ensure that all the goals are met. Another notable feature of the traffic calming strategies is that they are self-enforcing for vehicles (Harvey, 1992), rather than enforcing measures like speed limits. A speed bump, for example, cannot be avoided whereas speed limits may be breached. The benefits of traffic calming strategies include improving mobility and accessibility for non-motorised mobility, increasing safety and security on the streets, improving liveability (Soni and Soni, 2016) and reducing traffic accidents (Webster and Mackie, 1996).

Traffic calming strategies explored in four categories by Harvey (1992): (1) vertical deflections, (2) horizontal deflections, (3) road narrowing and (4) central islands (Harvey, 1992). Vertical deflections include road humps, speed bumps, speed cushion, raised crossings, raised intersections, uneven road surface and speed bumps (Pérez-Acebo et al., 2020). Some examples of horizontal deflections are kerb-extension, chicane, raised island, roundabout and gateway (Pérez-Acebo et al., 2020). Road narrowing measures are mostly supported by other measures as they are not sufficient to calm traffic on their own and perceived more as an encouraging factor to drive slowly (Harvey, 1992). Road narrowing examples consist of narrowing the carriageway, widening the footways, dedicating cycleways and formalising the parking spaces (e.g., creating a bus lane and stop). Central islands are also supported by other techniques, and they provide pedestrian refuges through creating surface or raised islands in intersections (Harvey, 1992). Additional to these categories, there are also supporting measures which consist of surface materials such as textured pavement, street furniture and streetscaping through plants and trees.

Pedestrian Exposure

Exposure is a term used to describe the potential for accidents when an individual becomes vulnerable to collisions (Chapman, 1973). Pedestrian exposure can be expressed as a variable representing the probability of risk and can be used in the simulation of traffic accidents (Lam et al., 2014; Qin and Ivan, 2001). The pedestrian exposure data is collected by examining the transportation system's set-up, such as physical facilities, users and the environment (Keall, 1995). However, it is usually challenging to collect and quantify pedestrian exposure because of the complexity of pedestrians' route choices (Lam et al., 2014). Once the pedestrian exposure has been established, the pedestrians' safety can be enhanced by the implementation of the appropriate interventions.

The interventions on pedestrian exposure aim to encourage walking by improving safety, minimizing behaviours that lead to accidents by reducing exposure time and making the street more inviting to the pedestrian by making it safer to cross the road (Zegeer et al., 2002). One example of this can be reducing pedestrians' exposure time to the potential risks by implementing shorter pedestrian crossings or extending the kerb. Refuge islands placed in the centre of the street can be another approach to reduce the pedestrians' exposure time, offering protection in the middle of a crossing.

The interventions which aim to reduce pedestrian exposure can be separated into four segments based on their objectives: (1) pedestrian facility design, (2) roadway design, (3) traffic calming and (4) signals and signs (Zegeer et al., 2002). The pedestrian facility design includes pedestrian overpasses and pedestrian underpasses. Roadway design interventions are road narrowing, reducing the number of lanes, refuge or pedestrian crossing island. Traffic calming interventions which reduce exposure consist of kerb extension, choker and refuge island. Pedestrian signal timings and accessible pedestrian signals form the signals and signs segment.

Visibility

The improvement of visibility plays a crucial role in designing pedestrian-friendly and safe environments (Sisiopiku and Akin, 2003). One of the main reasons for pedestrian fatalities is poor visibility of pedestrians (Shinar, 1984). Visibility refers to increasing the mutual awareness of one and another; it includes pedestrians' visibility for drivers, visibility of oncoming vehicles for pedestrians and visibility of the street infrastructure for both. Road users who are not seen can be left in unprotected and unsafe conditions.

Some of the measures which were taken into account when considering visibility are the range of vision, the visibility of pedestrian crossing signs, the visibility of pavement markings, the pedestrian crossing width, signalization of traffic direction, and lighting conditions of the street (Basile et al., 2010). Visibility depends on factors like natural light (day vs night), weather conditions, clothing, pedestrian movement, the driver (Zegeer et al., 2002). However, here, I will explain only the environment-oriented interventions for increasing visibility which include pavement extension, pedestrian refuge island, increase of traffic light timing etc.

Increasing visibility can be useful for several reasons. For example, environment-oriented interventions can help adjust drivers' speeding behaviour, increase drivers' perception, predict pedestrians' movement (Bella and Silvestri, 2015) and increase pedestrians' viewshed (Transport for London, 2020). These interventions primarily focus on providing a safe environment by making both parties, pedestrians and drivers, aware of each other through increasing visibility. Some examples of environment-oriented interventions are pedestrian refuge island, traffic light timing, car parking prohibition (Basile et al., 2010), advanced yield lines (Bella and Silvestri, 2015), high visibility pedestrian crossing (Kar and Blankenship, 2009; Sarwar et al., 2017), right slip lane angle (Zegeer et al., 2002), street lamps (Kwan and Mapstone, 2004), pavement extensions (Basile et al., 2010), warning lamps, locating street furniture in a way that does not interfere with visibility, arranging plantation on the lines of sight of each observer, street shape, locations of intersections, camber and inflexion of street. These examples are most of the time provided during the planning stage of the street. However, examples like pavement extension (Bella and Silvestri, 2015), the addition of refuge island or traffic light timing (Basile et al., 2010) can be reconfigured at later stages.

Pedestrian Behaviour and Desire Lines

Desire line is the term used to refer to the paths that are intuitive, explorative, habitual that operate in a different direction from the lines formally determined in the city (Furman, 2012).

In urban planning, it has been used for representing the straight lines connecting the trips' origins and destination points (Throgmorton and Eckstein, 2000), rather less poetically. However, since then, the term has been defined in a variety of ways depending on the context. In this research, the desire line refers to the informal paths and tracks generated over time by walkers' preference and feet, which differentiates from the official (pre-planned, designed or paved) routes (Smith and Walters, 2018; Tiessen, 2007). This kind of description is interpreted differently by various authors. In some articles, authors referred to this form of spatial and temporal non-compliance behaviour as illegal (jaywalking), risk-taking behaviour (Ishaque and Noland, 2008) or urban *meanderthals* (Tiessen, 2007). On the other hand, some have also viewed it as a productive force (based on desire theory of Deleuze and Guattari (1977), Smith and Walters (2018)), "human text" (de Certeau, 1984), an easily measurable behaviour (Throgmorton and Eckstein, 2000) or as an ultimate design tool for building space for humans (Angel et al., 1975).

Depending on how the behaviours are perceived, the interventions related to desire lines diverge accordingly, such as encouraging or constraining them. When desire lines are considered as a space-building tool, the aim is to ensure continuity of the path based on the pedestrians' movement patterns, locate nodal elements (squares, parks, crossings) and distribute the generators (parking facilities, transit terminals, residential areas etc.) (Stuart, 1968). The desire lines are aimed to increase time efficiency, reduce waiting time, reduce travel distance (Saxena et al., 2020) and exploration of alternative routes (Smith and Walters, 2018). In order to facilitate the direct movement of pedestrians, the potential interventions to be introduced include kerb extension (to provide a degree of comfort for pedestrian traffic), the enhancement of pedestrian crossing, the reconstruction of intersection (for safety and locating crossings on desire lines), the improvement of wayfinding signs and the development of links that favour walking over other modes of transport, the implementation of signal-controlled crossing point, the replacement of overpasses and underpasses with pedestrian crossings, the use of traffic speed reduction measures to facilitate informal crossings (in appropriate locations), the minimization of waiting times, the planning of various pedestrian route choices and the formalisation of the footpath surface by raising, painting or texturing it (Transport for London, 2020). When these measures are not provided it is likely that people will follow their preferred desire lines (Transport for London, 2020).

Another type of approach to the movement on these lines is restricting or discouraging as local authorities would not want them to cause potential hazards and risks such as falls or collisions with another road user (Saxena et al., 2020). This approach included interventions such as installation of barriers (such as guard rail) (Department for Transport, 1995), dropped kerbs as a deviation from desire lines (Philipotts, 2015), warning and direction signs also used to divert pedestrians from desire lines in the event of construction or road work (Saxena et al., 2020).

Previous Classifications of Pedestrian Street Interventions

In the literature, the classification of pedestrian street interventions (or in some pedestrian facilities) has been practised to guide urban and transport planners in shaping streets. The classification of interventions in the literature has been set out in a number of ways: (1) area-specific classification (kerbside, crossing, layout, footway, carriageway) (Department for Transport, 2007; Transport for London, 2019), (2) user-oriented classification (pedestrians, cyclists, public transport users etc.) (Department for Transport, 2007), (3) objective-oriented classification (informative, regulative, warning etc.) (Department for Transport, 2018; Zegeer et al., 2002), (4) classification by the type of closure (full, half or diagonal) (Leeds University, n.d.), and (5) classification by function of intervention (vertical deflection, horizontal deflection, narrowings etc.) (Falamarzi et al., 2014).

Area-specific classifications are found in two documents. One of them is the Streetscape Guidance prepared by Transport for London (2019). Here they grouped the interventions as footway amenities, the quality of footways, the carriageways, the crossings, the kerbside, the safety and functionality and the street infrastructure.

In the other example, the Manual for Streets, Department for Transport (2007) grouped the interventions first according to the *street users' needs*, and then an area-specific categorization was carried out for each user group. For example, they categorized the pedestrian-related interventions under the subjects of layout, surfaces, crossings, pedestrian links, and footways.

Objective-oriented classification examples include more specific intervention groups such as traffic signs (Department for Transport, 2018) and a more general classification of pedestrian intervention by Zegeer et al. (2002) (Figure 2.1). The Department for Transport (2018) has divided traffic signs into five groups; informative, regulative, warning, road markings, traffic control and temporary (e.g. road works and emergencies) signs. Zegeer et al. (2002), in their Pedestrian Facilities Users Guide, grouped the pedestrian interventions at a more macro level. The guide provides 47 enhancements for pedestrians, which have been established in order to achieve specific objectives such as the reduction of vehicle speed, the reduction of pedestrian exposure, the improvement of visibility, the reduction of vehicle volumes, the improvement of pedestrian access and mobility, the promotion of walking through aesthetics, the improvement of compliance with traffic rules and the removal of behaviours which lead to crashes.

Leeds (n.d.) has categorised traffic calming measures according to their *closure type* (Figure 2.2). They separated closures into full closure, half closure, and diagonal diverters. Half closure represents the barriers that cover the part of the street for a short distance, sometimes called partial closure. A full closure is the barriers placed across the carriageway to block the street completely. Diagonal diversion refers to diverting motor vehicles in one direction and prohibiting other directions.

Another classification of traffic calming measures was provided by Falamarzi et al. (2014) (Figure 2.3). They chose to classify the traffic calming strategies according to *their functions.* These functions included vertical deflections, horizontal deflections, narrowings, pavement treatments, parking management, volume control, streetscaping, changes in speed limit, enforcement, special zones, traffic signs, improvement of street infrastructure and network analysis.

In urban studies, permeability is used to distinguish between public and private spaces and measure the continuity of pathways (Alonso de Andrade et al., 2018). In my research, permeability is used as the extent to which the street intervention permits or limits pedestrians' movement. The reason to choose permeability is to assess the intervention's impact on pedestrians via understanding mediating factors of spatial and temporal extents.

Interventions influence the movement patterns, and the temporal and spatial distribution of road users. Although some of them aim to restrict some aspects of space over certain periods of time, many also encourage the use of a certain space in other periods. The spatial constraints of the street are clarified here by the concept of permeability, while the temporal aspects are presented in the next section under temporal permeability.

In urban and transport planning, permeability refers to the degree to which the design of urban forms permits or restricts the movement of people or vehicles in various directions (Department for Transport, 2007). Urban forms used here affect movement patterns such as continuity of paths, choice of routes, the nodal elements such as squares, small parks or public transport stops and the distribution of generators such as position or coordination of links (Stuart, 1968). While permeability and connectivity are used interchangeably in this context, there are noticeable subtle distinctions between the two concepts (Marshall, 2004, p.89). The key difference is that connectivity investigates the number of links in the street network whilst permeability aims to explore what permits or restricts the movement. For example, a pedestrian light can be seen as a connection whilst it is only permeable for pedestrians when it is green. Another example is when a pedestrian crossing's width increases its connectivity does not change whilst permeability increases as it allows space for more pedestrians to cross.

Analysing space based on the connectivity and integration of the areas is the method used in studies such as space syntax, a term introduced by Hillier and Hanson (1984). These studies include a larger spatial analysis which covers a network of streets. However, as Marshall, (2004, p.199) states, walking journeys cover short-distances and a limited range of journeys. Therefore, separate from the literature of space syntax, in this taxonomic analysis, my discussion of permeability focused on the smaller scale by looking into the street interventions.

In my research, permeability is defined as the effect of street interventions permitting or limiting pedestrian movement. Permeability, as a concept, helps us to understand the affordance (Gibson, 1979; further explained in Chapter 3) of the space that the pedestrian navigates. The pedestrian desire to move is predictable to a certain extent, in that they can be assumed to prefer to go where there are fewer interruptions to their path and where it is more convenient e.g. short distance, shorter time etc. (Furman, 2012). Looking into the permeability of interventions discovers how the street network influences pedestrian and vehicular movements, which in turn, affects the character of the interaction and behaviour of pedestrians and the occurrence of risk-taking behaviour on the street.

Pedestrian navigation is affected by particular constraints and encouragements in street space, provided by the interventions that urban planners make (as discussed above, Pedestrian Street Interventions section). These constraints and encouragements are addressed in my research not simply as spatial, but also as temporal. This approach, combining the spatial and temporal impact of interventions, helps to understand these impacts more fully and so aids us to build the street infrastructure in a more pedestrian-oriented manner.

Objective	A. Pedestrian facility design	B. Roadway design	C. Intersection design
1. Reduce speed of motor vehicles		- add bike lane / shoulder - road narrowing - reduce number of lanes - driveway improvement - curb radius reduction - right-turn slip lane	- modern roundabouts
Use in conjunction with other treatments	- street furniture		
2. Improve sight distance and visibility for motor vehicles and pedestrians	- crosswalk enhancements - roadway lighting - move poles / newspaper boxes at street corners	- add bike lane / shoulder	
3. Reduce volume of motor vehicles		- reduce number of lanes	
4. Reduce exposure for pedestrians	- overpasses / underpasses	- reduce road narrowing - reduce number of lanes - raised median - pedestrian crossing island	
5. Improve pedestrian access and mobility	- sidewalk / walkway - curb ramps - crosswalk enhancements - transit stop treatments - overpasses / underpasses	- raised median	
6. Encourage walking by improving aesthetics	- street furniture - roadway lighting - landscaping options	- raised median	
7. Improve compliance with traffic laws			- red light cameras
8. Eliminate behaviours that lead to crashes			- red light cameras

D. Traffic calming	E. Traffic management	F. Signals and signs	G. Other measures
- curb extension - choker - chicane - mini-circle - speed humps - speed table - raised pedestrian crossing - raised intersection - driveway link / serpentine - woonerf		- signal enhancement (e.g. adjust signal timing for motor vehicles)	- speed-monitoring trailer - school zone improvement
- landscape options - paving treatments		- sign improvement	
- curb extension - speed table - raised pedestrian crossing - raised intersection - paving treatments		- sign improvement (e.g. warning sign) - advanced stop lines	
- woonerf	- diverters - full street closure - partial street closure - pedestrian street		
- curb extension - choker - pedestrian crossing island		- pedestrian signal timing - accessible pedestrian signal	
- choker - pedestrian crossing island		- traffic signal - signal enhancement - accessible pedestrian signal - pedestrian signal timing	
- gateway - landscaping - paving treatments			-identify neighbourhood
- traffic calming: choker, chicane, mini-circle, speed hump, speed table			- speed-monitoring trailer - pedestrian / driver education - Police enforcement
- traffic calming: choker, chicane, mini-circle, speed hump, speed table		- pedestrian signal timing	- pedestrian / driver education - Police enforcement

Figure 2.1. Classification of Pedestrian Facilities according to their Objectives. Image recreated from Zegeer et al. (2002).

Segregation	Full Closures	Half Closures	Diagonal Diverters
(Volume Control)	Median Barriers	Forced Turn Signals	One Way
Integration	Speed Bumps	- Round-top humps - Flat-top humps - Sinusoidal profile humps - 'H' road humps - 'S' road humps - Thermoplastic hump ('thumps') - Speed cushion - Mechanical humps	
(Speed Control)	Speed Tables	Raised Crosswalks	
	Raised Intersections	Textured Pavement	Intersection Islands
	Roundabouts	Chicanes	Realigned Intersections
	Intersection Narrowings	Pinch Points	Centre Island Narrowings
	Chokers	Gateways	Planting
	Street Furniture	Bar Markings	Rumble Devices (Rumblewave)
	Mini Roundabouts		

Figure 2.2. Classification of Traffic Calming Measures according to their Closure Types Image recreated from Leeds University, (n.d.).

Strategies	Measures
Vertical deflections	Speed bumps, speed humps, speed tables, speed cushion, rumble strips, and raised crosswalks/intersections
Horizontal deflections	Chicane, lateral shift, central chicane, and traffic circle
Narrowing	Choker, neck-down, road-diet, sidewalk widening, pedestrian refuge island, hatched marking, turn lane, and median
Pavement treatment	Brick paving, stone paving, and colored surface
Parking management	Parking restriction/prohibition, nonparallel parking
Volume control	Half closures, full closure, diagonal diverters, and turn prohibition
Streetscaping	Street furniture, tree planting, and gateway
Changes in speed limit	School zone, speed limit reduction, and truck speed limit
Enforcement	Police enforcement, increased punishment, and speed cameras
Special zones	Truck exclusion zone, shared space, pedestrian zone, and school zone
Traffic signs	Warning signs, regulatory signs, school signs, bicycle signs, pedestrian signs, residential signs, truck signs, special zone signs, and traffic calming signs
Improvement of street infrastructure	Crosswalk, sidewalk, bike lane, and street lighting
Network analysis	Changing street direction from one-way to two-way (or vice versa) and changing direction of a one-way street

Figure 2.3. Classification of Traffic Calming Measures according to their function. Image from Falamarzi et al. (2014).

Temporal Permeability

Temporal permeability formulates a new angle on an under-observed quality of permeability in street environments. In the literature, permeability is normally considered as a long-term attribute of the street and as a quality embedded in the space. However, permeability is a temporary variable when we look further than a connected street network. When pedestrians are walking, they make decisions based on complex events that involve a variety of influences such as vehicle dynamics, traffic characteristics and environmental conditions (Zhang and Fricker, 2021). The complexity of these events comes from their changing conditions, such as a pedestrian signal changing from the "do not walk" to "walk" phase. These kinds of localised changes in various temporal durations affect the behaviour and actions of the pedestrians. That is, in part, why I will be looking at the temporal aspects of permeability. I will also show that other aspects of temporality are important.

I assess the temporal permeability of pedestrian interventions by analysing the time allocated to these spatial structures to direct or influence the pedestrian movements. Activity choices emerge from the spatial and temporal affordance of the pedestrian interventions. Every action pedestrians take in the environment is a steering process for deficits in the spatiotemporal environment as they perceive and encounter that environment. This section explores particularly the interventions which change the temporal dimension of permeability while affecting the pedestrians' movements on the street.

The longevity of an intervention and its reaction-time are two temporal dimensions of permeability. Longevity can be explored based on whether the intervention is long-term or short-term. Long-term interventions, here gathered under the heading of *static permeability*, are formalised, permanent and fixed interventions. Short-term interventions, which are classified under *transient permeability*, aim to repurpose the space temporarily or change in the space. The interventions which have reaction time are discussed under *dynamic permeability*. Reaction-time refers to the time between the interaction (or actuation) with the intervention and the intervention's response. The interaction or actuation in these types of interventions can be driven by a clock which begins a routine cycle, or it can be started by the users. To summarise:

- <u>Static Permeability:</u> Static permeability refers to those interventions that have invariable accessibility when implemented. They are intended to exist over a prolonged period and do not change their response to restrict, permit or promote access to a particular area on the street.

- Transient Permeability: Transient permeability refers to the interventions that afford invariable accessibility for a limited time, such as day, week, or month. These interventions can be introduced in order to respond to certain situations. However, their response is intended to last longer periods than the dynamic permeability interventions, and the range of responses they offer does not change. One of the most important distinctions between transient permeability and others is that transient permeability is impermanent and is planned to be removed or replaced in the space.
- Dynamic Permeability: Dynamic permeability refers to interventions that afford a range of responses on a periodic basis. They change their state and respond to conditions. These interventions are designed to operate over a long period, however, they tend to elicit various responses, and their responses are ephemeral as they react to the present situations. Therefore, their responses vary depending on the condition that triggers that response.

A Method to Analyse Street Interventions

This section of the research develops a methodology for examining pedestrian interventions through their spatial and temporal qualities. The aim is to facilitate the process of thinking about, and responding to, major aspects of temporal permeability. This thought process helps to explore the pedestrian interventions' potential impact on pedestrians' daily interactions with the street. To this end, the taxonomic analysis was guided by the following research questions:

1. How does a street intervention change the distribution of different types of road users? Does the street intervention increase the relative space dedicated to pedestrians, vehicles or cyclists?
2. How does a street intervention impact the "allowed" or "permitted" paths? Does the street intervention cause a discontinuity or create a longer path for the pedestrians?
3. How does a street intervention affect the capacity of the pedestrian space? Does it reduce or increase the space through its implementation?
4. What is the planned duration time for these interventions? Or how long does the intervention last?
5. Does the intervention have a response? If so, what is the response and how long is the reaction time?

Answering these questions requires a multi-dimensional assessment of pedestrian interventions. Giving a framework helps the researcher to clarify what will be included and how

it is going to be studied. It also reveals the relationship of main variables (Gray, 2014). Based on the descriptions of the terms
provided in the previous section, I here offer a framework for responding to these questions in a systematic manner (Table 2.1). This framework serves as a guiding map that links the terms and fundamental concepts of temporal permeability to the questions posed.

Questions		Does the intervention change its condition? or What is the planned duration for the intervention?				
		Dynamic		***Transient***		***Static***
1. Does the intervention change the distribution of road users to benefit pedestrians?	***Permeability Increased***					
2. Does the intervention have the possibility to limit in a certain direction?	***Unchanged Permeability***					
3. If the answer is yes, what level of flexibility does it provide?	***Permeability Decreased***					

Table 2.1: A Framework for Analysing Temporal Permeability

The framework is used to evaluate the temporal qualities in the table's horizontal axis and evaluate the permeability related qualities in the table's vertical axis. One of the main issues while establishing a framework is to ensure that each intervention analysis fits unambiguously within the defined units, but this is not always achievable. In order to define the interventions appropriately, the framework therefore contained "on hold" spaces in between the defined terms. These "on hold" spaces can be used as discussion points where the interventions' spatial and temporal qualities are debatable. In the next section, the framework is used to analyse the existing examples of pedestrian interventions from the literature. Finally, in the results and discussion section, this chapter develops a map based on the spatiotemporal permeability analysis to demonstrate the distribution of pedestrian interventions.

The Temporal Permeability of Pedestrian Interventions: A Discussion Based on Existing Practical Examples

This section categorises practical examples based on the literature discussed in the previous section. The categories are traffic calming strategies, pedestrian exposure, visibility, pedestrian behaviour and desire line strategies. At the end of this section, there is also a group of examples that do not fit into any of the previously listed categories.

Practical Examples from Traffic Calming Strategies

Traffic calming strategies were explored in four categories as discussed at the beginning of this chapter. Here the examples are grouped under the subsections called vertical deflections, horizontal deflections and supporting measures. Vertical deflections include examples of intersection reconstruction and raised crossings. Horizontal deflections include pavement widening, pedestrian refuge and barriers to reduce the distance which pedestrians cross. Supporting measures include streetscaping, parklets and traffic barriers.

Practical Examples of Vertical Deflections for Traffic Calming Strategies

<u>Intersection Reconstruction:</u> Figure 2.4 shows an example of intersection reconstruction for safety purposes. The example uses a tactical urbanism tool, paint. While the intersection is reconstructed with paint, it is also supported with other elements (such as plants, bicycle rack, street furniture etc) to promote the space dedicated to pedestrians. Since it is a tactical urbanism example, it could be classed as transient; however, it is worth mentioning here, in that it also includes static elements such as street furniture, bicycle rack. The permeability is increased because the availability of space for pedestrians is increased. The environment does not have any responsive elements and that is why it is not considered as dynamic.

<u>Raised Pedestrian Crossing:</u> Raised crossing is an intervention which provides a crossing at the same level as the pavement (Figure 2.5). While it elevates the pedestrian, it also slows down the vehicular traffic. While this intervention increases the perception of pedestrian safety, it does not significantly change the permeability level of the street for pedestrians. Raised crossing, in this research, is classified under the static and unchanged permeability categories.

Image redacted for copyright reasons.

Image screenshot of: https://blog.urbanfile.org/2019/09/19/milano-urbanistica-piazze-aperte-inaugurazioni-e-nuove-proposte/

Figure 2.4. An example of Intersection Reconstruction near Primaria Ciresola. Image from NoLo Piazza, Milano, Italy, (2019).

Figure 2.5. Raised Pedestrian Crossing in Sydney. Image from Levinson (2020).

Practical Examples of Horizontal Deflections for Traffic Calming Strategies

Pavement Widening: Pavement widening is a way of narrowing the roadway and reducing the crossing distance by providing extension of the pavement area into the parking or driving lane. It increases the permeability for pedestrians as it increases the space dedicated to them. The temporal aspect of pavement widening interventions changes according to its type.

a) Pavement widening through removable structures: If the pavement widening is implemented through removable structures such as barriers etc., then it is transient (Figure 2.6 & 2.7).
b) Pavement Widening through Painting: If the pavement widening included painting, then, I positioned it in between the permanent and transient, as it can be easily removable but at the same time it can be renewable (Figure 2.8).
c) Pavement Widening through Construction: If the pavement widening interventions include structural components that need to be (semi-)permanently secured then these interventions fall in the scope of static interventions (Figure 2.9).

Pedestrian Refuge: The pedestrian refuge dedicates an in-between space separated from oncoming traffic. It aims to reduce the crossing distance by dividing the crossing into two stages and in each, the pedestrians can focus on one direction of traffic at a time. Since it creates a space for pedestrians in the middle of the road, the pedestrian refuge can be included under the category of increased permeability. The pedestrian refuge can be implemented in two ways; (1) as a raised pedestrian refuge or (2) painted pedestrian refuge.

a) Raised Pedestrian Refuge: Raised pedestrian refuge is implemented to be static and permanent. It provides space for pedestrians, so it is classified here as increased permeability (Figure 2.10).
b) Painted Pedestrian Refuge: Painted pedestrian refuge can be implemented to be removable or permanent through renewing the paint. That is why I would place it in a temporal classification in between the transient and static. Even though it provides additional space for pedestrians on the street, since this small space is provided only through paint, it can be disregarded by drivers, as seen in the image. That is why this intervention is categorized as in-between unchanged and increased permeability (Figure 2.11).

Barriers to Reduce the Distance that the Pedestrian Crosses: These barriers are most often removable structures that aim to reduce the crossing distance for pedestrians. They provide more area dedicated to pedestrians which increases the permeability of the street for them. The barriers can be categorized as transient since they are not implemented permanently. Barriers do not have any dynamic properties which generate responses towards the road users.

Image redacted for copyright reasons.

Image screenshot of: http://urbanplacesandspaces.blogspot.com/2020/06/

Figure 2.6. Colourful Pavement Widening. (Trueform Group and Layman, 2020).

Image redacted for copyright reasons.

Image screenshot of: https://twitter.com/raphaelzy3/status/1251477686289084418

Figure 2.7. Pavement widening through removable barriers, Barnes High Street, London, UK. Image from ZY (2020).

Image redacted for copyright reasons.

Image screenshot of: http://iqc.ou.edu/2017/05/31/buenosaires/

Figure 2.8. Pavement widening through painting in Buenos Aires.
Image from Hampton (2017).

Image redacted for copyright reasons.

Image screenshot of:

https://twitter.com/andrew_barr/status/1302884768367947777

Figure 2.9. Pavement widening through construction, Glasgow, United Kingdom.
Image from Barr (2020).

Image redacted for copyright reasons.

Image screenshot of: https://islandpress.org/books/urban-bikeway-design-guide-second-edition

Figure 2.10. Raised Pedestrian Refuge Example. Image from Urban Bikeway Design Guide, NACTO, (2014).

Image redacted for copyright reasons.

Image screenshot of:

https://twitter.com/iBikeCommute/status/1174104343789723654

Figure 2.11. Painted Pedestrian Refuge Example in Denver, United States.
Image from Mintzer (2019).

Image redacted for copyright reasons.

Image screenshot of:

https://twitter.com/robertburns73/status/1295309236289888256

Figure 2.12. Dundrum Interventions which reduce the distance of crossing, Dublin, Ireland.
Image from Burns (2020).

Practical Examples of Supporting Measures for Traffic Calming Strategies

Streetscaping: An important aspect of streetscaping is the introduction of planters (Figure 2.13) and trees (Figure 2.14) sometimes combined with grass hedges and shrubs. This type of intervention aims to improve safety by strengthening movement patterns and corridors (Transport for London, 2019). Streetscaping provides a more pleasant environment and serves as a supporting measure in traffic calming treatments (Topp, 1989). It does not change its condition as they are implemented to be permanent and static. However, their impact on the road users can vary with time, such as providing shade during the summer and more light in the winter. They do not typically change the distribution of road users, but form a separation between users. This can limit the movement to certain directions. The intervention may reduce the connection between the road and pavement; nevertheless, it can be by-passed.

Parklets: Originating with San Francisco's parklet initiative, parklets (Figure 2.15 and Figure 2.16) are built to easily and inexpensively restore vacant areas of land and convert them into public space (Davidson, 2013). They can be divided into two groups: the ones which provide pavement extensions, others which are more like barriers between the pavement and road that define the space with amenities. This type of intervention is implemented to be removable. The intervention can change the distribution of road users depending on where it is applied. For example, most of the parklet examples are located on parking lanes with the purpose of extending the pavement to provide more space and amenities for pedestrians. The parklets create a separation between the road users. However, they also generally reduce the opportunities for pedestrians to move towards the road. The intervention can limit the connection between the road and pavement; some of the parklet implementations provide limited passage while other parklet examples are more flexible. If parklets are removable or portable, they can be grouped as a transient in terms of permeability. Additionally, it is worth noting that their usage by pedestrians can vary based on their design. They do not have a reaction-time as they do not generate any response towards road users.

Traffic Barriers (crash barriers, pedestrian guardrails): These structures (Figure 2.17) aim to keep the vehicles in the carriageway and prevent them from colliding with obstacles, trees, buildings or other structures. They are also used around pedestrian zones or around pedestrian refuges. They have multiple types according to their functions, however they are generally continuous structures. They are not designed to be removable, and they do not change the distribution of road users. They do not have a reaction-time as they do not generate any response towards road users. Traffic barriers provide designated paths so they severely limit the route the pedestrians can follow.

Image redacted for copyright reasons.

Image screenshot of: https://www.nycstreetdesign.info/landscape/permanent-planter

Figure 2.13. Planters in 168th Street, Manhattan.
Image from New York City DOT (2019).

Image redacted for copyright reasons.

Image screenshot of:

https://www.seattle.gov/Images/Departments/Trees/PlantingAndCare/StreetTrees/streettrees.jpg

Figure 2.14. Trees on sides of the road.
Image from Seattle Municipality (n.d.)

Image redacted for copyright reasons.

Image screenshot of: https://www.dezeen.com/2015/11/28/portable-parklet-wmb-studio-greenery-bench-london-park/

Figure 2.15. Portable Parklet by WMB Studio in London, United Kingdom.
Image from Tucker (2015).

Figure 2.16. Parklet on 1331 9th Avenue, sponsored by Arizmendi Bakery.
Photo Credit: Jack Verdoni Architecture, (2011).

Image redacted for copyright reasons.

Image screenshot of:

https://cms.esi.info/Media/productImages/tn/174047_1570533951883_PF.jpg

Figure 2.17. Pedestrian Guardrails in London, United Kingdom.
Image from Image from ESI.info (n.d.).

Practical Examples for Pedestrian Exposure

Pedestrian exposure considers interventions which reduce the pedestrian exposure time. As mentioned in the literature review section, the potential intervention methods include shorter pedestrian crossings, extension of pavements, signal timings and quick responses from signals. The examples which are represented in traffic calming strategies, related to intersection construction, pavement extension, pedestrian refuge and barriers to reduce the distance which pedestrians cross, are also examples that contribute towards the reduction of pedestrian exposure. Since they are already discussed in the previous section, I will not discuss them here again.

Pedestrian overpass and underpass are examples related to pedestrian exposure as they remove the pedestrian from the road by providing another route. Street closure for motor vehicles is another example which removes the pedestrian exposure through a reverse strategy (removing vehicles from the road). X-Crossings (where pedestrians may cross a junction diagonally) reduce the time spent crossing the road by stopping vehicle traffic in all directions during the red light. Extra time for senior and disabled citizens provides an additional time for safe crossing and reduces the exposure of these groups to potential hazards. Smart crossings, smart surface and automated traffic light examples can potentially generate quick responses and adjust the signal timings to reduce pedestrian exposure as well.

Pedestrian Overpass and Underpass: Pedestrian overpass (Figure 2.18) is a permanent intervention. This type of intervention is expensive to introduce and has a low level of convenience. As previously discussed in the desire line segment of the Pedestrian Interventions section, pedestrians choose to take direct routes, and an indirect route, like a pedestrian overpass or underpass, is unlikely to be used. That is why most of the time they are coupled with guard-rails, effectively forcing pedestrians to use them. Even though a pedestrian overpass or underpass provides a new route not previously available to pedestrians, since it is mostly limiting and forcing pedestrians to choose a longer route the intervention is here categorised as in-between unchanged and reduced permeability.

Street Closure for Motor Vehicles: Street closure to motor vehicles (Figure 2.19 and Figure 2.20) can be a temporary intervention or long-term intervention according to need. For example, during the Covid-19 pandemic (beginning late 2019 / early 2020), street closure or road narrowing became very popular as a temporary intervention to assist social distancing. Generally street closures to motor vehicles are implemented for limited times so they are categorized as transient here.

Image redacted for copyright reasons.

Image screenshot of: https://cityobservatory.org/the-myth-of-pedestrian-infrastructure-in-a-world-of-cars/

Figure 2.18. Pedestrian Overpass for four lane highway, Port Wentworth, Georgia, U.S.A. Image from City Observatory and ICE (2020).

Image redacted for copyright reasons.

Image screenshot of: https://www.cnbc.com/2020/05/06/coronavirus-uk-social-distancing-set-to-transform-london-sidewalks.html

Figure 2.19. Street Closure for Motor Vehicles Camden High Street, London, UK. Image from from Frangoul (2020).

Image redacted for copyright reasons.

Image screenshot of: https://twitter.com/RailtonLTN/status/1311278302154371074

Figure 2.20. Street Closure for Motor Vehicles. Arodene Road, Tulse Hill, London, UK. Image from Railton LTN (2020).

Image redacted for copyright reasons.

Image screenshot of: https://www.youtube.com/watch?v=RAUjtqdONaY

Figure 2.21. X-Crossings used in Edmonton, Canada.
Image still from Edmonton Journal (2018).

Image redacted for copyright reasons.

Image screenshot of: https://theindependent.sg/lta-initiative-on-elderly-assistance-impresses-foreigners-part-of-singapores-effort-to-prepare-for-aging-population/

Figure 2.22. Extra time in crossings for senior citizens.
Image from Dziedzic (2019).

Since these types of interventions provide more space for pedestrians, they are located under increased permeability.

X-Crossings: X-crossings (also known as pedestrian scrambles) are a pedestrian crossing design which allows pedestrians to cross in any direction by stopping vehicles in all directions during the green light for pedestrians (Kattan et al., 2009). This intervention (example in Edmonton, Alberta in Figure 2.21) stops all traffic at once, to let people cross in any direction including diagonally when the pedestrian signal indicates walk. It provides connection in multiple directions during any crossing of the intersection, so it is categorized as increased permeability, and it is dynamically changing its condition, which is why it is classified under the dynamic category.

Extra Time for Crossing for Senior Citizens and Pedestrians with disabilities: The extra crossing time intervention in Figure 2.22 focuses on increasing the access to the crossing area for pedestrians with dedicated cards such as senior cards. The elderly pedestrians or pedestrians with disabilities can tap their card to have more time to cross the street. This intervention is classified in this research as in between the increased permeability and unchanged permeability as it gives additional time to certain groups of pedestrians. It is classified as dynamic as it is a responsive intervention.

Smart Crossing: Smart crossing systems (Figure 2.23) aim to respond to network demands in real time by improving flow-timing. The example from South Korea illustrated below works by alerting drivers when people are approaching and by warning pedestrians when there are vehicles nearby. In an alternative approach, in the UK, Transport for London is working on a crossing which increases the time dedicated to pedestrians by showing a green light for them until it detects a vehicle. These interventions increase the time dedicated to pedestrians to cross, so are categorized as increased permeability for pedestrians. Additionally, they change the condition to cross based on the current situation and so are categorized as dynamic.

Smart Surface: Smart surface intervention is a prototype for pedestrian crossing which uses computer vision to address safety issues on the road, developed by Umbrellium (2017) (Figure 2.24). It is a responsive system that adapts the markings and signals of the road dynamically in real-time by detecting, predicting and responding to changing conditions on the street. The intervention is able to modify patterns, layout and configuration of pedestrian crossings, so is classified here as increased permeability. Since it provides real-time changes in response to the conditions it goes under the dynamic category.

Automated Push Button: This intervention was developed by Glasgow City Council for Covid-19 to decrease the risk of contagion and to maintain physical distance by removing the touch point for users of the pedestrian crossing (Figure 2.25). The intervention does not increase or decrease the permeability of the street as it does not change the availability of the area for pedestrians. However, it removes a pain point, pressing the button, in the interaction through its automated system. Through this removal the experience of the pedestrian during the interaction can change from "asking a permission" or "communicating their intent" to "being recognised". In the taxonomy, it is categorized as dynamic because it has reactive qualities. Additionally, the reactive response is sensor-based rather than clock controlled.

Image redacted for copyright reasons.

Image screenshot of:

https://www.wired.co.uk/article/south-korea-smart-road-crossings

Figure 2.23. Smart Crossing, 2020. This crossing in South Korea alerts drivers when pedestrians are approaching, and vice versa. Image by Railston and Gamlen (2020).

Image redacted for copyright reasons.

Image screenshot of: https://umbrellium.co.uk/projects/starling-crossing/

Figure 2.24. Smart Surface by Umbrellium (2017).

Image redacted for copyright reasons.

Image screenshot of: https://www.dailymail.co.uk/news/article-8141575/Pedestrian-crossings-changed-forever-Sydney-amid-coronavirus-crisis.html

Figure 2.25. Automated Crossing. Image from Coë (2020).

Practical Examples for Visibility

Visibility aims to improve the visibility of pedestrians, environment and vehicles by increasing awareness of the road users. The intersection reconstruction (Figure 2.4) example from traffic calming strategies, discussed previously, enables greater visibility by formalising the space dedicated to pedestrians and using colours, street furniture etc. A raised crossing (Figure 2.5) increases awareness of vehicles through its thickness and signals them to slow down. Pavement extensions (Figure 2.6) can increase the visibility of pedestrians through helping vehicles to slow down while approaching (Vignali et al., 2020). The pedestrian refuge (Figure 2.10) is another environment-oriented intervention which increases the visibility of pedestrians through making the road narrower thus slowing the traffic and thereby allowing drivers more time-opportunity to see pedestrians (Vignali et al., 2020).

X-crossings, extra-time for senior and disabled citizens, smart crossing, smart surface and automated traffic lights are the other examples for increasing visibility for both vehicles and pedestrians as they regulate and provide a safe environment by making both parties aware of each other. Signs to increase pedestrian awareness, as their name suggests, increase the awareness of pedestrians by directing them where to look for vehicles. Textured pavement and smart tactile pavements are another indicator that pedestrians are approaching the road and should keep an eye out for oncoming vehicles. Painting crossings helps to formalize the crossing area and draw attention to it.

<u>Signs to Increase Pedestrian's Awareness:</u> Signs, such as look left or look right, are installed near crossings to alert pedestrians about potential dangers from moving vehicles through giving directions. These signs, in the UK, are made through writing on the road in front of the crossing area. These signs do not change the permeability for pedestrians as they do not change the spatial distribution of pedestrians nor create any limitation for them; rather they give pedestrians a direction to follow. They are easy to implement, renew and remove as they are made through painting.

<u>Textured Pavement:</u> They are static interventions, planned to be implemented for a long term. Tactile pavement is designed to help pedestrians with sight problems identify the pedestrian crossings. Textured pavement is a planned and permanent intervention so here it is classified as a static intervention. In terms of permeability, it is placed under the unchanged permeability as it does not change the permission and restriction to the space rather emphasizes where the pedestrian crossing is. This can increase its identification for some pedestrians such as

pedestrians with poor-sight. However, whether this would increase the permeability of the crossing for them is a debatable issue.

Smart Tactile Pavement: The smart tactile pavement (Figure 2.26) aims to use existing infrastructure and increase the awareness of pedestrians who use mobile phones by highlighting the traffic through their lighting system on the pavement, just before entering the crossing. The intervention does not affect the permeability of the road while it responds to the pedestrians dynamically.

Painted Pedestrian Crossing: Painting crossing lines (Figure 2.27) into an already defined area is used to emphasize the crossing area. The intervention does not change the amount of space dedicated to pedestrians or the limits the space pedestrians can reach. For this reason, the intervention is categorised under the unchanged permeability category. However, it impacts visibility and identifiability of the area and therefore its impact on permeability is open to discussion. The temporality of the intervention is located in between the transient and static, like other interventions which used painting.

Image redacted for copyright reasons.

Image screenshot of: https://www.dezeen.com/2016/07/28/movie-buro-north-ground-level-traffic-lights-prevent-pedestrian-accidents-video/

Figure 2.26. Smart Tactile Pavement from Büro North.
(Büro North, 2016).

Image redacted for copyright reasons.

Image screenshot of:

https://twitter.com/jen_keesmaat/status/726078440898715648

Figure 2.27. Painting Crossing Lines.
Image from Keesmaat (2016).

Practical Examples for Pedestrian Behaviour and Desire Lines

Pedestrian behaviour and desire line strategies aim to encourage or constrain the informal paths generated by pedestrians. They are intended to decrease delay time, waiting time, and distances. Intersection reconstruction (Figure 2.4) is one of the examples of pedestrian behaviour and desire line strategies as it reduces the travel distance and builds the space based on the pedestrian behaviours. Other examples are raised crossings (Figure 2.5) and pedestrian refuges (Figure 2.10) as it formalises the pedestrian crossing area. Pavement extensions (Figure 2.6) and barriers (Figure 2.12) also encourage and increase the free movement of pedestrians by reducing the travel distance between the pavements. Street closures for motor vehicles (Figure 2.19) increase route choice for pedestrians.

Another way to apply pedestrian behaviour and desire line strategies to the street is to incorporate signals through considering pedestrian behaviours. Consideration of the crossing time of elderly and disabled citizens, for example, is one of the implementations (Figure 2.22). Another one is to use X-crossings (Figure 2.21), which reduce the crossing distance and time. The examples for reducing the waiting time for pedestrians are smart crossings (Figure 2.23), smart surfaces (Figure 2.24) and automated traffic lights (Figure 2.25).

This category includes directional pedestrian crossings (Figure 2.28), which can minimize travel distance by eliminating the need for pedestrians to avoid oncoming pedestrians. Guerrilla crossings (Figure 2.29) are another example that is discussed here because they minimize travel distance and are built unofficially by road users based on their preferred routes.

Image redacted for copyright reasons.

Image screenshot of: https://100architects.com/project/the-chain-effect/

Figure 2.28. An approach for organising the pedestrian circulation on pedestrian crossings. Image from 100architects, (2018).

Image redacted for copyright reasons.

Image screenshot of: https://bikeportland.org/2009/12/28/guerrila-crosswalk-installed-on-east-burnside-27521

Figure 2.29. Mystery Crossing on E. Burnside at NE 8th.
Image from Klotz (2009).

Image redacted for copyright reasons.

Image screenshot of: https://popupcity.net/observations/urban-hacktivist-launches-guerrilla-crosswalks/

Figure 2.30. Guerrilla Crossing by urban hacktivist Florian Rivière in Strasbourg.
Image from Beekmans (2102).

Directional Pedestrian Crossing: The intervention illustrated above in Figure 2.28 is made by Anomaly + 100 Architects in China. It addresses the overcrowded zebra crossings in narrow streets in rush hours as people bump into each other while crossing in the opposite direction. To improve the pedestrian circulation on zebra crossings they implemented zig-zag lines to create arrow shapes to give pedestrians a directional hint which helps to divide the circulation in two. This intervention is categorized in-between the transient and static categories as it is applied through painting and in terms of permeability, it is classified as unchanged permeability as it does not increase the space, or the connection pedestrians have.

Guerrilla Crossings: Guerrilla crossings such as Figure 2.29 and 2.30 are a modification on the street made by unauthorised people. They are mostly made through paints however, there are other creative ways that people intervene in the environment such as urban hacktivist Florian Rivière. They are classified as a transient intervention as they are provided as a temporary change without jurisdictional approval. Since they provide a route for pedestrians, it is considered here under the increased permeability category.

Practical Examples which Do Not Fit Any Groups

These last two practical examples were not found appropriate for any of the groups presented above as they do not aim to calm traffic on the road, reduce pedestrian exposure, increase visibility or aim to encourage pedestrian behaviours or desire lines. The examples include pavement reduction through barriers and structures and anti-terror barriers.

Pavement Reduction: Pavement reduction through barriers most of the time is temporary intervention. When it is temporary, it is generally implemented for road work, emergency or for a public engagement. However, there are also long-term interventions to reduce the pavement to provide cycling lanes etc. For example, Figure 2.31 provides a cycleway through reducing the pavement which would be categorized as a static intervention. On the other hand, Figure 2.32 would be a temporary implementation of reducing pavement area as it is applied through the usage of removable elements. Pavement reduction related interventions always reduce the space available for pedestrians, so it is an example of reduced permeability.

Anti-terror Barriers: Anti-terror barriers include bollards and bulky barriers that aim to prevent vehicle-ramming terror attacks (Figure 2.33s). Anti-terror barriers do not change their condition or their position. They are implemented to be permanent/static. Anti-terror barriers do not change the balance of road users. It reduces the capacity of the space and limits the movement of pedestrians. This intervention again provides a by-passing option in a slightly more prolonged way than streetscaping interventions.

Image redacted for copyright reasons.

Image screenshot of:

https://twitter.com/JTUrbanDesign/status/1169320465170665473

Figure 2.31. Pedestrian Path Reduction Dublin, Ireland.
Image from Taylor (2019).

Image redacted for copyright reasons.

Image screenshot of: https://www.falkirkherald.co.uk/news/transport/falkirk-district-roadworks-brightons-grangemouth-and-maddiston-among-places-impacted-3132687

Figure 2.32. Footpath Closure for Roadworks, UK.
Image from Reilly and Devlin (2021).

Image redacted for copyright reasons.

Image screenshot of: https://www.thenationalnews.com/world/moped-gang-dodge-anti-terror-barriers-on-london-bridge-to-hit-pedestrian-1.618358

Figure 2.33. Anti-terror Barriers in London, United Kingdom.
Image from Andersen and AFP Photo (2017).

Discussion

In this section, I present a map to show the relative locations of the analysed interventions in the spatial and temporal dimensions. The purpose of positioning each intervention type is to help to understand and compare the spatial and temporal features of the interventions. This map allows us to determine the spatial and temporal extent of the interventions offered as they are implemented.

The map, based on the tabular framework introduced above (Table 1), is divided into three categories on each axis: on the temporal dimension, dynamic, transient and static; on the spatial dimension, increased permeability, unchanged permeability and decreased permeability. Additionally, the practical examples are grouped according to the literature presented previously. The groups include traffic calming strategies related interventions, pedestrian exposure-related interventions, visibility related interventions and pedestrian behaviours and desire lines related interventions. Furthermore, three interventions, including pavement reduction with barriers, anti-terror barriers and pavement reduction through structures, are seen to not fit into any of the four groups.

In the map, we can observe a tendency towards sensing pedestrians in the dynamic interventions category. Smart surface, smart crossing, extra time for crossing, automated push button and smart tactile pavement are in need of a certain level of pedestrian awareness to operate. These interventions operated through either sensing all pedestrians or groups of pedestrians such as senior pedestrians in the case of extra time for crossing. They sense mostly through specific sensors or are triggered through a tool, as again in the case of extra time for crossing, the intervention is triggered by a senior card.

Another tendency in this same group is the interventions provide a visual interface to interact (or communicate) with pedestrians. If they communicate a change in spatial distribution, they do it through their interface such as changing the signals. The change in the interface aims to inform the pedestrians or vehicles to act. That is why they play a more proactive but perhaps less preventative role in the negotiation of space than other groups. For instance, the static and transient intervention categories focus on the spatial distribution of the road user through physical structures. The interaction in these interventions is communicated through the absence or presence of these physical structures.

The map presented in Figure 2.34 shows that most of the interventions accumulate around the static and transient categories of the temporal section. It is interesting to note that while streets are unpredictable, temporary and fluid, the number of dynamic interventions with increased permeability is less than five. One of the arguments for dynamic and increased permeability interventions comes from the streets' need to address multiple road users and their agendas at the same time. These types of interventions can help to mediate the arrangements and interactions happening in the street to create a safer and more efficiently used street. Another argument is that pedestrians are already aware of the under-used, over-regulated and sometimes vacant spots of the street (which will be discussed further in Chapter 5). While regulatory measures are beneficial for certain groups of pedestrians, it should be also possible to reflect localised changes in various temporal durations to affect the behaviour and actions of pedestrians.

The intersection of decreased permeability and dynamic temporality is also not addressed by the many interventions I have looked at. This intersection represents potential ways of structuring the street in a car-centric approach. This of course is not the focus of this PhD. Additionally, dynamic structures presented here from time to time can reduce the permeability of the street for pedestrians as well (e.g., when the intervention does not allow their crossing action), however, I discussed their permeability by comparing a street without the intervention and with the intervention. That is why the interventions in the increased permeability are placed at the selected positions.

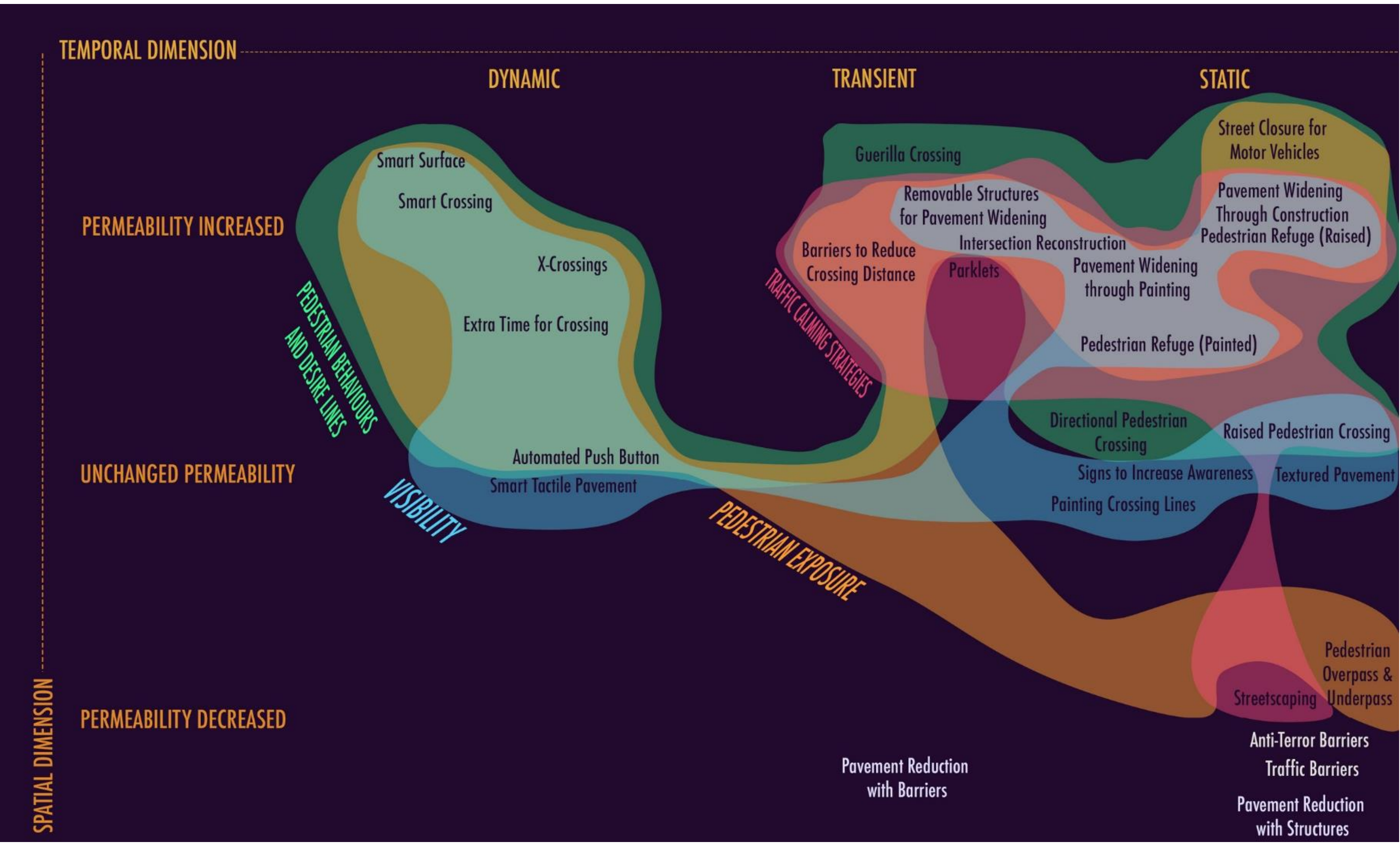


Figure 2.34. The map showing the Temporal Permeability of Practical Examples.

Research Questions

The goal of this thesis is to better understand pedestrian behaviour in the street environment and to propose spatial and temporal dynamic approach for managing street mobility that have the potential to improve pedestrian convenience and safety. This is intended to be accomplished by increasing their impact on the street by focusing on localised changes in the environment in order to empower pedestrians. This PhD therefore asks: how to design a pedestrian centric street system that dynamically manages street mobility?

Dynamic and pedestrian centric street system, here, refers to a procedural and responsive process to organise and interact with pedestrians and other road users, leveraging the pedestrians' position in the street in the system rather than protecting them through static and inflexible street structures that limit their abilities. The procedural part of the process would help analyse a greater scale of pedestrian data, whilst the responsive element would help communicate what data indicates with the road users.

Designing this kind of system depends on the answers to a series of subsidiary questions about pedestrian data and the employability of this kind of system. Which pedestrian data would the intervention be dependent on? What behaviour occurs in the real world and what influences pedestrian behaviours? How can we evaluate the impact of this kind of implementation in the street? Where can we test this kind of intervention? These questions will be expanded on and answered in the remainder of the thesis.

Chapter 3 Theoretical Framework

Congestion, pollution, social inequity and other issues connected to traffic transportation are becoming increasingly common in cities today (Nieuwenhuijsen, 2020). Human-powered transport, such as walking and cycling, is being promoted as a potential answer to these issues (Cox, 2008; Godefrooij et al., 2009; Iravani and Rao, 2020; Santilli et al., 2021) . One of the particular interests of current research on human-powered transport is pedestrian-oriented approaches of urban and transport planning fields. In the literature, the shift from car-centric to pedestrian-centric practices has mainly focused on spatial measures of the built environment that affect the system, such as pavement conditions, land use, and route connectivity as it is explained in Chapter 2. Thus far, there has been little practical implementation focusing on spatiotemporal issues, such as pedestrian's interaction with vehicles, that may have the potential to elevate and improve their daily mobility.

Walkability, pedestrian-centric initiatives, traffic calming, pedestrian level of service, and shared space concepts have traditionally been used to characterise interventions that target pedestrians (Explained in Chapter 1: Introduction). These concepts primarily address the problems through spatial planning and interventions. With technological innovations such as smart cities, autonomous vehicles, internet of things, the approaches towards achieving ideal cities are changing (Kumar et al., 2020; Nikitas et al., 2020; Zanella et al., 2014). The importance is centred around gathering real-time data, making sense of this data, connecting and managing the street based on the data. Where pedestrians are located in this new era of urban mobility planning is not fully explored yet. The new generation of pedestrian-centric thinking must tackle not only the spatial but also the temporal position of pedestrians and address a wide range of needs and preferences. In-depth research on the subject is required to better understand pedestrians' situational needs and preferences during their journey. Increasing the emphasis on pedestrian activities may help build more rigorous practices in current street contexts. This approach might help influence future interventions, planning practices, and policy objectives.

My research aims to improve the understanding of pedestrians' actions in the street environment and propose spatial and temporal dynamic approaches to manage street mobility that have the potential to increase pedestrians' convenience and safety. In the previous section, I have identified the research question of how to design a pedestrian centric street system that dynamically manages street mobility. This question brings two key concepts forward: (1) pedestrian-centric thinking and (2) dynamic approaches.

This chapter provides a framework to address this question by considering a number of concepts, theories and design principles. The following sections discuss two shifts: (1) from car-centric thinking to pedestrian-centric thinking, and (2) from static strategies to dynamic approaches. These sections aim to explore the field of inquiry by discussing the key terms. The first one includes human-centric design and the theory of affordances as key concepts. The second one contains dynamic system approaches such as complexity, adaptation, responsiveness. In these sections, I summarise the models, strategies, and frameworks used to contextualise the former approaches. In the subsequent section called *Establishing the Studie*s, I will discuss how I have employed these concepts to explore the research question.

Reframing the Street

In the below section "*From Car-Centric to Pedestrian-Centric"*, the definition of pedestrian-centric is connected with the concept of human-centred design and the theory of affordances. The second shift, "From Static to Dynamic Approaches", includes complexity, adaptation and responsiveness. I will evaluate these concepts in the context of the street and mobility.

From Car-Centric to Pedestrian-Centric Thinking:

The aim of the pedestrian-centric approach is to promote walking over vehicle use to reach safe, less-congested, sustainable cities and healthier citizens. There are two primary fields relevant to pedestrian mobility in the scope of this PhD: (1) urban studies and (2) transport studies.

In urban studies, there have been various approaches such as walkability, shared space and strategies such as the healthy street approach. The focus of these approaches is most often protected pedestrian paths (Gonzalez-Urango et al., 2020), street network analysis (e.g. D'Orso and Migliore, 2020), the density of streets and pedestrians (e.g. Dovey and Pafka, 2020; Jiao et al., 2021), access to other mobility options (e.g. Tinessa et al., 2021) and the presence of walking facilities (e.g. Majumdar et al., 2021; Shatu and Yigitcanlar, 2018). Blitz and Lanzendorf (2020) extensive review of the literature on the subject of non-motorised mobility also concludes that the focus of the urban planning approaches mainly revolved around street network analysis, land use, and the presence of walking and cycling facilities. Building on this argument further, it is clear that the dominant theme in these examples is the focus on spatial qualities of the street (with a particular emphasis on pedestrian-only zones). On the other hand, pedestrian and vehicle tension, and the interconnected issues raised by this tension such as safety and maintaining permeability for pedestrians, are underexplored in the urban studies.

In transport studies, there is a long history to develop transport policies and engineering solutions affecting pedestrians and their relationship with vehicles. These attempts aim to balance the desire to maintain traffic flow with the need for pedestrian safety. However, in most circumstances, the desire to keep traffic flowing exceeds the issue of how to reduce the delay for pedestrians while offering safe alternatives (Ishaque and Noland, 2008). This can be seen through some examples given in Chapter 2 such as overpasses, underpasses, guardrails. Even the new green man code noted in Chapter 1 – though it is an improvement from the current situation and perceived by many motorists (Bird, 2021; Hawker, 2021) as a setback for motor vehicles – does not really challenge car-centric thinking, as the idea supports arranging the green light for pedestrians around the absence of vehicular traffic. To summarise, although pedestrian-vehicle interaction has been empirically studied by different disciplines and methodologies (e.g., transportation engineering, traffic psychology, safety science), attempts towards exploring these interactions to achieve (or design) a pedestrian-centric street mobility system are lacking through the literature. This need is explained by Hydén (2021) as a lack of holistic solutions that can safeguard pedestrians while making their life more attractive.

Urban studies indicate a gap regarding pedestrian and vehicle interactions while transport studies lack pedestrian-centric thinking. Providing these gaps would primarily contribute to the goal of making streets safer for pedestrians while potentially increasing the number of pedestrians who inhibit streets without a single-minded focus on facilitating traffic flow. Therefore, I have decided to take a pedestrian-centric, and systemic approach, with the aim of incorporating pedestrian behaviours and interactions with vehicles to maintain and safeguard pedestrian movement. Through this approach, my goal is to increase the representation of pedestrians in the street mobility system.

Pedestrian-centric, also known as pedestrian-friendly, pedestrian-oriented, are terms used loosely in various ways in the literature to refer to different aspects of urban space, mobility or infrastructure. Liu et al. (2015) uses pedestrian-oriented as a term to define the warning system that uses smartphones- which looks like more of a system that is smartphone-oriented or in other examples it is used interchangeably with walkability concept. To avoid this confusion, in the following sections I will explore the theoretical underpinnings of the pedestrian-centric approach in this PhD.

In this research, the pedestrian-centric approach is defined as an approach to design street mobility systems and to increase safety while providing a level of convenience for pedestrian movement. My focus is the pedestrian use of the street through understanding the relations between the pedestrian's capabilities and the situational and spatial context of the street. Tyler (2021) defines capability as the gap between the capabilities of a person and the capabilities that an environment requires to perform a certain activity. In parallel to this definition, by pedestrian capabilities, I mean that an individual handles situations and the street environment in order to arrive at a certain location in a certain time and in relation to other criteria (such as what environment offers or requires). This definition refers to concepts of human-centric design and the theory of affordances which I will be exploring next.

Human-Centred Design: Human-centred design has its roots in human factors, computer science and ergonomics. The international standard ISO 9231-210 defines human-centred design as an 'approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics and usability knowledge and techniques' (International Organization for Standardization [ISO], 2019). Although this approach to human-centred design proved to be useful in addressing technical problems, this definition primarily describes applications in engineering and science that improve usability objectives of a product (in other words, usability engineering) (van der Bijl-Brouwer and Dorst, 2017). One of the concerns related to this approach is its tendency to assert predetermined functions and assumptions about the design context (Giacomin, 2014) as it does not consider the contextual and situational circumstances (van der Bijl-Brouwer and Dorst, 2017). This leads to a reductive representation of 'the human' by ignoring the importance of situated action. This issue is particularly criticised by Suchman (1987, p.179) who emphasised the importance of situated action by defining it as an 'emergent property of the moment-by-moment interactions' between actors and their surroundings.

In the context of my research, the term "situated action" refers to pedestrian behaviour and interactions with their surroundings such as infrastructures, other pedestrians and vehicles. By considering the behaviour and its contexts, my goal is to understand cause and effect relationships through the street. I use the term "context" to refer to the circumstances that shape a pedestrian's response to a certain event in the environment. An illustrative example in the street can be the changing positions of vehicles in relation to pedestrian behaviours. Through situating their actions, I intend to obtain a deeper level of understanding about the variations amongst pedestrians in order to represent them through the design processes of simulation and intervention.

One of the challenges of the context-oriented approach is that although the data is rich, it does not provide straightforward answers to designers. Various scholars have argued that there is a gap between user research and design practice (Norman, 2010; Wixon, 2003). There are a number of principles to close this gap such as scenario-based design which uses user cases, personas and customer journey to collect opinions of users, participatory interventions to help users to get into the designer's world, and empathy stimulating techniques to invite designers to the user's world such as role-playing, storytelling, experience prototypes (Giacomin, 2014).

One of the issues about these techniques, that came across through the literature, is the problem of innovation. Norman and Verganti (2014) state that the human-centred design techniques often explore incremental innovations, 'doing better what we already do'. It has been argued by a number of researchers that they lead to incremental improvements enabling people to improve their experiences of existing solutions, but not to radical change that would enable them to change what they do (Norman and Verganti, 2014; van der Bijl-Brouwer and Dorst, 2017). The argument is that they rely on people's existing knowledge and experiences of certain products and therefore, designers get more trapped into the existing paradigms.

As Choi et al. (2016) argue, the human-centric approach in the street context is expected to promote active travel while conventional street design is expected to primarily serve automobiles. In this paradigm, by focusing primarily on environmental transformation, the pedestrian-centric approach does not challenge the current limits of street mobility. This approach results in continuous modifications of the environment which is conventionally car centric. Hence, an incremental change such as shift of focus may not be addressed through solely rethinking the current nature of pedestrians. Creative new approaches or tools that can reconsider the street environment through pedestrians would be needed to bridge the gap between rich observation and design practice.

Therefore, in my research, human-centred design is used in a slightly different way, as proposed by Giacomin (2014), referring to examples and definitions of Pullin (2009), 'who accepts the need for problem solving, but who emphasises instead openness of mind, the challenging of existing constraints and the influencing of behaviours and social structures'. Human-centred design, here, is used to understand the existing meanings of pedestrian interactions and behaviours in traffic and then using them to challenge the existing constraints in the street. In relation to understanding the existing meanings of pedestrian interactions and behaviours, the next section will look into the theory of affordances.

<u>Theory of Affordances:</u> Gibson (1966, p.285) coined the term affordances as part of the theory of perception. He defined perception as a link between human capabilities, the proclivity to act, and what the environment offers to support. He generalised this theory to all animals and defined it as "the affordances of the environment are what it offers the animal, what it provides or furnishes for good or ill". This definition ties the affordances to what humans can do with their body (Krippendorff, 2005), what the environment offers and limits and what the individual perceives.

The use (and meaning) of affordance theory changed when it was introduced by Norman (1988) in his book "The Psychology of Everyday Things". He defines affordances as a likelihood of an individual to use an object in a way it is designed to and whether the object 'suggests' how the object should be interacted with. This approach to affordances is a limited one as it does not address the complementarity of the individual, environment and the artifact in use by focusing solely on the relationship between the product and individual. This results in employing the theory of affordances to design artefacts that guide users through their recognisable features. This approach to the theory of affordances differs from Gibson's explanation through focusing on usability instead of utility. It is more related to the practical design problems which may explain its widespread adoption in the fields of human-computer interaction, user-centred design and interaction design. Later on, in his recent versions of the same book (Norman, 2013), Norman distinguishes affordances as perceived affordances and further elaborates the designer's vision of affordances as signifiers.

As Annunziata and Garau (2020) stated, 'the concept of affordance is relational, situational and dynamic'. My focus, in this research, is looking into situational affordances in the street. By situational affordances, I mean how pedestrians act under certain situations (e.g., when they are in conflict with a fast car vs. slow car) and how their actions differ. Situationality refers to the events during their negotiations with vehicles when they need to cross the street. Therefore, the situational affordances are described through the spatiotemporal environment that guides the actions of pedestrians. And further analysis looked into what actions individuals employ through their perception process.

In this research, I use Gibson's version of affordances as it has proved more useful for conceptualising how pedestrians use the situations in the environment to make a decision to cross. Gibson's original affordance theory draws attention to the fit of artefact or environment to the activity of the user (or in other words utility). Unlike Norman, Gibson does not define a 'correct' usage for the environment or an artifact. Therefore, 'correctness' of pedestrian use, or how the street is supposed to be used, was not an issue in this study. Rather, the focus was on what was happening in the environment, how the events around them were affecting pedestrians' use of the street, and what actions they were performing as a response.

The theory of affordances previously has been addressed in street and urban environments through focusing on the impact of the built environment on human behaviour (e.g. Annunziata and Garau, 2020; Furman, 2017). Furman (2017), for example, used affordances to discuss how we adapt and change the urban environment to be comfortable via street design and use. Similarly, Annunziata and Garau (2020) referred to affordances as functional, social and emotional opportunities and restrictions built into a space in connection to different groups of people. They further investigated the usage of the theory of affordances in the concept of walkability and framed it to conceptualise the relationship between the individual and the environment. The goal of this conceptualisation is to create accessibility as well as functional, social, emotional affordances of a place.

In this PhD, through observational investigation, I have explored situational affordances in the environment. Using Gibson's interpretation of affordances, I intend to define the role of situations in the street (such as incoming vehicles, traffic light conditions and actions of other pedestrians) on pedestrian's decision to move across the space.

From Static to Dynamic Approaches

In the theoretical aspect, investigating links between physical elements in the street and human activities has received considerable interest across a variety of disciplines (Chen et al., 2009; Lynch, 1964; Tuan, 1979). These links are derived from studying the physical aspects of urban areas, such as environmental affordances of streets. Despite the fact that they investigated human behaviour in order to assess the spatial and physical aspects of the street, the main focus is on comprehending the urban physical environment. I refer to this approach as static, and I take an alternative approach by considering the interactions, behaviours and situational context of pedestrians: the dynamic approach.

While static approaches can be valuable in estimating human mobility through urban physical environments, my research focus is on temporal and situational variations, exemplified by pedestrian crossing behaviours. Through its dynamic approach, this research aims to understand reciprocal interactions between the vehicle, pedestrian and environment, how the behaviours are shaped based on the situational context of these interactions and how the understanding of these interactions can be used to intervene and shape street mobility. The dynamic approach is used in two ways in this research: (1) evaluating the street mobility dynamics through study of pedestrians and, (2) designing a dynamic intervention for pedestrian-centric street mobility.

The first one focuses on tracking and recreating the reciprocal conflicts between pedestrians and vehicles, local pedestrian behaviours and their situational context. It indicates the necessity of discovering multiple forces at work in situations where pedestrians need to make a decision (in this research, it is particularly about crossing decisions). This approach is explained by Loaiza-Monsalve and Riascos (2019) through emphasising the importance of understanding human mobility dynamics when you want to affect the various aspects such as urban planning, traffic optimisation, and sustainability. Some sources suggest that through this activity, pedestrians must make an adapted decision that necessitates a good comprehension of the situation of the street in the temporal and spatial constraints (Payne et al., 1992). On the other hand, others point out that it is probable that in some cases the decision-making process in this situation may lack strategy or thoughtfulness (for example when automatic behaviour occurs in which pedestrians follow the others) (Cœugnet et al., 2019).

The second part looks into dynamic interventions in the street context. These interventions are concerned with the functional aim of facilitating the movement of people and goods, allowing access to the spaces and serving as places for social interaction. According to Jacobs and Appleyard (1987), this can be achieved by creating a comfortable, safe and meaningful space. In the previous chapter (Chapter 2, Literature Review), I discussed dynamic interventions that address pedestrians such as smart crossings, automated push buttons, and smart tactile pavements. In this research, I aim to use a dynamic approach towards street interventions to open up a discussion and explore the opportunities and limitations it offers. Additionally, I need to understand how they can be moved from conceptual to applicable as well as what would be their potential impact. In the next subsections, I will be discussing the concepts of complexity, adaptation and responsiveness.

Complexity: Complexity is a derivative of the Latin root *complexus* which is described by Oxford English Dictionary (2021) as “whole comprehending in its compass a number of parts, esp. (in later use) of interconnected parts or involved particulars; a complex or complicated whole”. It is defined by a large number of interconnected components, the interactions of which occur in a variety of ways and follow local rules, implying that no valid higher command exists to describe the different possible interactions (Johnson, 2004). There are different levels of complexity in the urban mobility system. For example, it contains volumes, diversity and synchronicity of urban mobility components such as motorised vehicles, pedestrians, infrastructure and information systems that are interacting with each other (Al Maghraoui et al., 2017). Another complexity is in the variety of options of use as well as different combinations of this use (Al Maghraoui et al., 2017). In this research, I mainly discuss complexity from the pedestrian perspective.

It is complex to communicate with pedestrians and understand their intentions (Rasouli et al., 2018). This complexity comes not only from their nonverbal behaviours such as their body movements, head orientations and movement but also from the complexity of the context in which they are monitored. Therefore, it is crucial to understand their context in order to grasp their behaviours (Rasouli et al., 2018). Here, I define pedestrian mobility and their decisions during crossing as a complex system, because even though there are certain instructions defining the various ways of interacting such as traffic rules, these rules may not be applicable in certain situations. Specifically, crossing the street as a pedestrian deals with a number of interactions, environment and temporal constraints and finding opportunities.

In the literature, there are a number of studies that address the complexity of pedestrian behaviours and their studies which focus on complexity of the environment (D'Acci, 2019; Park and Garcia, 2020; Tapiro et al., 2020), complexity of pedestrian behaviours (Cœugnet et al., 2019; Rasouli et al., 2018) and interactions in traffic scenes (Cloutier et al., 2017; Merlino and Mondada, 2019). In terms of environmental complexity, D'Acci (2019) investigated the link between spatial complexity and the pedestrian's route choice. Tapiro et al. (2020), on the other hand, focused on visual complexity and explored its implications on road crossing behaviour. In research related to pedestrian behaviours, Cœugnet et al. (2019) classified pedestrian decision-making during their crossing period and the dynamics of this activity as complex. Rasouli et al. (2018) covered complexities in traffic scenarios, scenes in urban environments, street crossings and the associated perceptions. The interactions of traffic scenes touched on similar topics as the studies on complexity of pedestrian behaviours. They emphasised complexity of crossing processes, street traffic configurations, and local measures (Merlino and Mondada, 2019) as well as the cognitive complexity of pedestrian behaviours and complex movement dynamics (Cloutier et al., 2017).

Road users, as mentioned by Al Maghraoui et al. (2017), play a key role in forming the street's dynamics and street's performance. They conclude that systemic modelling - formalising an integrated design process for urban mobility system - can allow us to identify the links between the components (e.g., road users, volume of vehicles, infrastructure) of the urban mobility system. In this PhD, complexity is used to define interdependencies, interactions, and diversity of street mobility systems that introduce uncertainty and unpredictability. This definition leads to exploring adaptation and responsiveness concepts within the context of complexity. Therefore, I approach the complexity of pedestrian interactions in the street via adaptation to recognise and avoid conflicts, as well as to explore advantages that situations provide in the street.

Complexity is studied by dissecting the phenomena at hand into logically justified individual elements or components (subsystems) (Crooks et al., 2019, p.3) - for example, studying flocking behaviour through identifying individual starling movements and interactions. This strategy is a bottom-up approach - meaning that the complex system in question emerges by building the subsystems and their interactions (Macal, 2016). In order to understand the complexity, we need methods or tools that can recreate the mechanisms and behaviours that form the complex systems (Crooks et al., 2019, pp.5-9). Agent-based modelling presents the most promising approach as it provides a comprehensive framework for capturing the interdependence, interactions and diverse behaviours of complex systems (Crooks et al., 2019, p.9). I will be discussing further agent-based modelling and its use on pedestrian simulations in the Chapter 6.

<u>Adaptation:</u> The concept of adaptation is approached by a number of disciplines. In biology, it is defined as the process whereby an organism fits itself to its environment (Goumopoulos et al., 2008; Holland, 1995). In complexity science, Heylighen (2002) describes adaptation as the capacity of a system to adapt its changing environments without harming its fundamental organisation. Gershenson (2007) expands this definition as a change in an agent or system as a reaction to the state of its surroundings that can help to achieve its objectives. All the stated descriptions emphasise an adjustment to change, and adaptation defined as a modification of the system to compensate for any divergence from its objectives.

Flexibility of an agent or the system that can increase the usability by adjusting its content to changing conditions is one function of adaptation (Hou et al., 2014). And this flexibility is also connected to the understanding of the data and feeding it into other processes. This understanding is managed by the system through deciding when, what, how and how much adaptation is needed and adjusting its outputs accordingly (Hou et al., 2014). This can be achieved through two ways: through a response mechanism (feedback) or anticipation mechanism (feedforward) (Gershenson et al., 2016). Whilst response mechanisms handle a posteriori using feedback, anticipation mechanisms handle the adaptation by predicting using feedforward mechanisms. Since predictability is limited in complex systems, I will focus on using response mechanisms (or feedback) for adaptation in this research.

Adaptation in the domain of urban mobility and planning is applied in various ways, from mobility services to lighting systems. For example, Boonstra and Boelens (2011) approached spatial mobility using adaptive initiatives emerging from dynamics of society. On the other hand, in mobility, Bucchiarone (2019) considered adaptation beneficial for managing and organising mobility services. They considered adaptation in the context of on-demand mobility service. On the other hand, Lakehal et al. (2021) explored creating adaptive pedestrian behaviour for navigation skills and wayfinding process. More practical implementations of adaptation concepts varied from adaptive street lighting systems (Shahzad et al., 2016) to adaptive geographic information services for pedestrian navigation (Zipf and Jöst, 2006).

In this research, I aim to use the concept of adaptation in two ways: (1) to explore pedestrians' adaptation to the environment, (2) to explore how street mobility can adapt to pedestrian behaviours. While the first one looks into the different behaviours given by pedestrians to changing situations, the second one looks into how to form a pedestrian-centric street mobility by considering their convenience and safety. Specifically, the latter use of adaptation introduces the concept of responsiveness and feedback, therefore I will be looking at the concept of responsiveness in the next section.

Responsiveness: Responsiveness is described, in this research, as a tool for adaptation that facilitates the goal of the system. This can be achieved through responsive mechanisms that incorporate feedback to communicate with and affect the human. This mechanism is similarly described by Krueger (1977) as a system which perceives human behaviour and responds with feedback. The responsiveness comes from the idea of street mobility as a complex and dynamic system that can respond to pedestrians and other road users and can modify itself.

Such responsiveness would require understanding the dependencies between the space, system and human behaviour (Yamashiro and Hidaka, 2006). In this context, responsiveness is connected with the terms *feedback* for perception and action of the system and *interaction* as an impact on and communication with the human. Feedback is the process between the cause and effect that holds the system components together (Heylighen, 2002). Interaction is the kind of outcome that is a result of this feedback process.

In urban mobility, the word 'interactive' is often used more to describe context-aware responsive interventions. For example, Pan and Gao (2020) used interaction to provide information to citizens about travel and traffic information based on their individual needs. Tu et al. (2016) used Internet of Things as a way to create interactive digital signage to engage with the people that are context-aware and able to make recommendations to travellers. The practical examples in Chapter 2 under the dynamic section such as smart tactile pavement, smart crossing or smart surface are also other examples of using responsiveness in urban mobility that collects information from the context and interacts with users.

As the examples show, a responsive approach needs an understanding of the dynamics in the environment in order to intervene in the actions and perception of the people (Yamashiro and Hidaka, 2006). In this research, since I focus on situational elements that affect pedestrians, responsiveness aims to inform and interact with road users through its understanding of the temporal patterns of pedestrian actions.

Establishing The Studies

Transitioning towards a pedestrian-centric and dynamic street system will require not only design implementation but also new practices of planning. In the previous chapter, I have identified the research question as to *how to design a pedestrian centric street system that dynamically manages street mobility*. In this perspective, the role of pedestrian factors (especially considering human behaviours and behavioural processes) becomes fundamental in the context of the street mobility system. Nevertheless, there are certain challenges about *how to design* this dynamic system and *how to experiment* with the designed systems in order to improve it.

How to design this dynamic system looks into the sense-making part of the research. Herbert Simon (1969) in *The Sciences of the Artificial* starts his definition of design as "concerned with how things ought to be …". It is clear we need to make a certain judgement as a designer to construct meaning, a sense of things or a definition (Manzini, 2015). This exploration of meaning construction occurred in all three studies through the thesis, first during the stage of understanding the context, then reconstructing this context and at last by intervening to context in order to challenge its constraints.

The previous studies about understanding the behaviour of pedestrians during their crossing period used accident data for analysing road safety (e.g. Rolison, 2020), motion tracking for analysing positions of pedestrians (e.g. Zhang et al., 2020), observational methods through mainly employing videography data (Kathuria and Vedagiri, 2020; Liu et al., 2017; Ni et al., 2016), detection and tracking techniques by using LiDAR sensors (Wang et al., 2017; Zhao et al., 2019). The common point of the way these methods have been employed was the insights collected from these studies. They were most often representing quantitative differences about how pedestrians act in certain situations. For example, distance, pattern, time to collision were used by Kathuria and Vedagiri (2020), whilst Ni et al. (2016) created interaction patterns based on the speed. On the other hand, one aspect which is lacking through the literature is the pedestrian's process of crossing and the relationship between this process and the context in which they act. In this research, I aim to use observational techniques to understand the behavioural process of pedestrians and their situational context.

Following on from Simon's (1969) opening definition of design, he continues "... how they ought to be in order to attain goals and to function". Manzini (2015, p.34-35) expands on Simon's definition through defining the role of design as strategic when the problem is not clearly defined. This strategic approach entails identifying the problems and portraying them in a way that makes them easy to understand: problem shaping. This problem shaping is also mentioned in *From Car-centric to Pedestrian-centric Approaches* section under the *Human-Centred Design* in another form, as a gap between the user research and design practice.

Previous studies in design addressed this gap in a number of ways such as customer journeys, participatory interventions, storytelling and experience prototypes. While these techniques are beneficial in the latter phases of the design process, the goal of my research, which is to challenge existing constraints of pedestrian mobility in the street, would require a more open platform where early experiments and iterations of those experiments can be demonstrated and discussed. I will discuss the specific experimentation and iteration techniques that I used in my research in the next chapter.

In the previous section 'From Static to Dynamic Approach', I discuss interacting components of the street through complexity, adaptation and responsiveness concepts. The higher level of complexity in street mobility, which needs to include pedestrian's interactions, intentions, constraints and opportunities, is what I have aimed to represent through the research. Therefore, a more systemic approach towards understanding this complexity is secured through these concepts. This led me to exploring to find methods, tools and techniques that can represent these concepts and create an appropriate environment for experimentation. This part aimed to address the research sub-questions of *'What pedestrian data would the intervention be dependent on?"*, '*How can we evaluate the impact of interventions in the street?'*, and *'Where can we experiment with the interventions?"*

Human behaviour and urban mobility studies deal with complexity and include approaching the subject using agent-based modelling simulation techniques (e.g. Jia et al., 2012; Qu et al., 2019; Wise et al., 2017). This technique has proved useful due to its bottom-up approach and its ability to represent a wide range of individuals at the systemic level. However, in these studies, the experimentation was primarily focused on pre-existing environments such as metro stations (e.g. Qu et al., 2019) or spatially explicit models using geographic information systems (GIS) (e.g. Crooks et al., 2019). Additionally, they were based on quantitative analysis (e.g. Liu et al., 2017), assumptions (e.g. Sargoni and Manley, 2020) or secondary research (e.g. Xi and Son, 2012). In this PhD, I instead investigate how simulation can be employed throughout the experimentation phase, as well as the relationship between data collection and data implementation techniques. This relationship has the potential to help us better comprehend pedestrian behavioural processes and represent their behaviours at the systemic level. In the next chapter, I will be explaining these methods in further detail, describing them, their relationship, how they are employed in this research, their limitations and how these are addressed.

Chapter 4 Methodology

Design is a circular, conversational process (Glanville, 2003, p.22).

In this chapter, I develop a methodological approach in order to undertake design research to address my research question *"how to design a pedestrian centric street system that dynamically manages street mobility*". As I have mentioned in Chapter 3, I investigated this question through two sub-sections: (1) how to experiment and (2) how to design. My approach to these questions largely comes from research through design and second-order cybernetics. Before describing my process, it is helpful to give some context on research through design and second-order cybernetics and how they are interrelated.

Methodological Approaches

Research through Design (RtD)

Frayling (1993) defines research through design, one of three design modalities, as "what is being achieved and communicated through the activities of design". The origin of research through design is rooted in the Royal College of Art through the work of Bruce Archer (1995). He suggests that "there are circumstances where the best or only way to shed light on proposition, a principle, a material, a process or a function is to attempt to construct something, or to enact something, calculated to explore, embody or test it" (p.11). This is a suggestion that I have pursued in my work by exploring, constructing and testing processes and propositions.

This course of action enables designers to transform and reform their approach towards the problem in question (Archer, 1968). This falls into the category of *problem shaping*, addressing the gap between research and practice (referring back to Chapter 3) or *problem setting* as Schön (1983, p.40) puts it. These terms capture the idea that the process between the problem and solution is not straightforward, especially if the problem is concerned with real-world practices. Schön (1983, p.49) suggests that "our knowing is in our action"; therefore, he suggests the *reflection in action* approach which involves framing and clarifying the problem through acting. This implies a process of constant iteration by acting through analysis, synthesis, evaluation and construction where there is an information flow through reflective loops (Dorst and Cross, 2001). It brings out the tentative nature of design which is not only associated with acting for correction and improvement but also provocation for further questioning (Boyd Davis and Vane, 2019).

This research takes a research through design approach by developing practice on two levels: (1) observational inquiry feeding into the design of a tool for designing and (2) iterative design and development of a tool for designing. These two levels approach the research question by addressing (1) *how to experiment* and (2) *how to design*. The first part, *how to experiment*, is addressed by translating the observational inquiry into a simulation tool through exploration, framing, recreating, and analysis. Creating this tool aimed to provide information and insights that researchers and designers can use when designing for pedestrians to reframe and reflect on their ideas or practice. The second part, *how to design*, aimed to show the process of reframing and reflection on the idea that is presented here, *dynamic street interventions*.

Second-Order Cybernetics

Cybernetics comes from the Greek word κυβερνήτης, steersman, (+ics) and is concerned with communication and control systems in living organisms and machines (Oxford English Dictionary, n.d.). Wiener (1948) combined communication with control in his first book and stated that communities can only be understood through the study of communication facilities and messages between human or machine agencies. He defined cybernetics as a science which focuses on understanding how systems use information, models and control actions to achieve their goals despite the various disturbances such as external actors (Wiener, 1954). Cybernetics focuses on goal-directed and functional systems which require a certain degree of control (Heylighen and Joslyn, 2001). The main element in cybernetics is feedback. The theory of cybernetics is based on feedback loops which steer the system towards its goal.

Feedback is what holds together the system components in what may be a nonlinear relationship where the relation between cause and effect is not straightforward (Heylighen, 2001). For example, small causes can have large effects and vice versa. Feedback loops tie the system components in through a circular process. This circular cycle can be explained as any change in the first component fed back to the first component itself via its impact on the other components (Heylighen, 2001). There are normally considered to be two types of feedback: positive and negative. For a healthy system, it is suggested that both types of feedback should take place (Bird, 2003). With both types of feedback, the system can have, in some sense, an awareness of its surroundings.

Second-order cybernetics, also known as the cybernetics of cybernetics (Mead, 1968; von Foerster, 2003), introduces a second loop to cybernetics which looks at the relationship between the observer and observed. Through accepting the role of the observer, second-order cybernetics connects with the reflective practice mentioned in the RtD section above. The presence of an observer takes the concept of feedback and circularity at the core of the cybernetic system and extends it: there is then not only the circularity of the system but also the circularity of the act of observing (Glanville, 2003, p.6). This recognises that the observer's observation constructs the system and decides what aspects of the system are relevant or irrelevant (Heylighen and Joslyn, 2001). Thus, the system properties differ with the model of the observer.

A variant on the cybernetic approach is offered by through his Conversation Theory where he constructs a model of 'conversational' interaction that focuses on meditation through shared meanings. Conversation Theory offers a model of how interaction leads to constructing "knowledge" or "knowing" by emphasizing the requirement of conversation for understanding different perspectives. Conversation requires a series of interactions that aims to reduce the differences until agreement is reached. Learning occurs through conversations about a subject matter which serves to make knowledge explicit. This theory resembles how I conducted the agent-based modelling where I constructed the simulation through a 'conversation' between me as a researcher and the model. This 'conversation' included translating the video into the simulation, reflecting on and comparing the simulation with the video. Through this process, I aimed to increase the resemblance between the pedestrian agents in the simulation and pedestrians in the video, while also deepening my own knowledge. Referring to Glanville's (2007) paper, my research iterates between failures and steering away from these failures with my understanding and perception as a researcher and observer. Through this circular and reflective process, my goal is to close the gap between the video observation and simulation.

In this PhD, the two sub-questions on 'how to design' and 'how to experiment' use the concepts of iteration, circular feedback and the presence of an observer. The questions both refer to iterating by designing, implementing, constructing and understanding. In addition, the inherent interaction between them refers to the feedback between the processes. The role of observer in the research process explains the role of me as a researcher, who moves between the studies in order to reflect and to construct knowledge and practice. The moving between the studies serves to change perspectives especially when defining the collected data and experimenting with the design intervention.

Constructing the Studies:

My approach to addressing the research question is characterised through three studies and their iterative and circular relationship. Before explaining the process, first, I would like to discuss the methods I have used for these studies and their aim. The first study aimed to collect and analyse data. This serves to enhance the understanding of pedestrian behaviours, interactions and their context during their crossing period and act as a reference for creating a tool for experimentation. The second study aimed to recreate a selection of the observed phenomena in order to expand the understanding and construct a tool for experimentation. The last study aimed to design an intervention and experiment with this intervention with the constructed tool. Whilst all three studies aimed to contribute to explore the 'how to design' aspect of the research question, the first two studies aimed to answer the 'how to experiment' part.

Conducting Qualitative Observational Study

This study aimed to answer *what are the pedestrian dynamics in the street* through looking into human behaviours, interactions and negotiations by emphasising the spatial and temporal relations of these actions. This is performed through an observational study that is a combination of qualitative and visual analysis of the behavioural process of pedestrians and their situational context. By behavioural process, I mean the sequence of pedestrian behaviours during their crossing period that is generated in response to the situational context and hence affected by temporal, spatial, vehicular activities occurring in the environment. Defining this process, I believe, would help to understand which situations affords which behaviours and how different people form different meanings through their actions into the space. Understanding these different processes is useful for this research, as they bring heterogeneity to pedestrian studies.

<u>Collecting Audiovisual Data:</u> Researchers, particularly in anthropology (e.g. Bateson et al., 1942) and sociology (e.g. Albrecht, 1985), have found recording techniques such as video, film, and photography useful in observing and understanding human behaviours. One motivation for using audiovisual recordings as observation tools, according to Erickson (2011), is that they allow researchers to systematically study the process of people informing one another through verbal or nonverbal cues. Siegman and Feldstein (1987) define nonverbal cues as "all behaviours that are involved in the transmission of experience or information from one person to another (or others)". These are especially challenging to capture with other methods, since using an alternative communication method to inquire into a behaviour – such as describing a visual event through verbal description – can limit the representation of it (Gray and Malins, 2017, p.95). Therefore, when collecting primary data, isolating nonverbal behaviour and spatial interactions between people such as proxemics, as well as showing the links constructed

through body language or movement, are important features of observational research (Rosenstein, 2002).

Audiovisual records also can help to capture the natural sequences of events and behaviours in their ordinary habitats (Timberlake and Silva, 1994). This is enabled through the method's closeness to the phenomena under study, allowing for a high degree of detail (Flyvbjerg, 2011, p.132-134; Hillnhütter, 2021). These fine level details can enable researchers to explain the logic between actions and the surroundings (Hillnhütter, 2021). To understand these details, video data also needs thorough analysis. Using the playback feature of video enables access to fine details of behaviour and interaction that may not be available in more traditional research methods (Heath et al., 2010, p.2; Oliveira et al., 2000). This is especially useful in complex environments such as streets where multiple entities change their conditions in parallel, as they allow researchers to analyse each entity separately. Repeated analysis makes it possible to capture the moments the human eye could miss (Rosenstein, 2002). Rosenstein (2002) emphasises the researcher's responsibility: video recordings can be valuable in defining the nature and importance of behaviour in responsible detail.

The use of video recordings in behavioural observation offers numerous advantages to understanding complex behaviour, the relationships between the behaviours (Haidet et al., 2009) and their context (Timberlake and Silva, 1994). Through choosing video recording to collect data about pedestrians, I aimed to focus on the natural sequences of events in the real world. Thus, this method of data collection helped to identify the behaviours and their spatial and temporal situations in a sequential manner. The strength of video recording in giving fine details of behaviours and interactions has been useful in understanding pedestrian negotiations in the street environment while considering the larger environment they are in. Preferring video recordings in this PhD over other types of data collection has allowed me to capture the nonverbal behaviours and movements of pedestrians during their perception and action process. This is especially important when investigating the pedestrians' responses, activities, change of behaviours that are represented through their actions.

One of the limitations associated with the use of video recording is ensuring privacy when data sharing and publishing the data. Whilst video data provides flexibility in the presentation and use of data, Heath et al. (2010, p.129) point out that sharing of video data can raise certain ethical concerns for data that was collected for research purposes. However, the data sharing can be arranged to preserve anonymity such as making people blurred so subjects cannot be identified from the published material.

Another concern with video recordings is the challenges in using and setting up video equipment. When setting up the equipment, Haidet et al. (2009) recommend considering the intrusiveness of recording equipment, the likelihood of greater individual reaction, and the loss of the wider environmental background beyond the view of the lens. According to them, these issues can be addressed by engaging experienced professionals to set up and run the video recording equipment or deploying additional tools or techniques to capture the larger environment.

I tested different ways of recording pedestrians to find the best way to capture their behavioural process and their surroundings. Some of the shooting styles I have tried included following different pedestrians in the selected area and recording data from the front window of the vehicles (passenger seat or front of the double decker bus). However, these were not useful as the first recording method was most of the time causing me to miss crossing behaviours and not giving a steady view, whilst the second method was giving a driver's perspective of pedestrians and not capturing well the moments where pedestrians decide. As a result, I decided to use a view where there is a clear view of pedestrians, traffic lights and vehicles around the pedestrians. This provided a closer perspective to pedestrians compared to other ways. Pedestrians have recognised the camera in a few instances, however this usually happened after they had crossed the street.

A different limitation of using video observation of natural behaviours in the real environment is that it is not possible to do a controlled experiment to measure potential scenarios and different measures (Lanzer et al., 2021). If the observations are conducted in a controlled environment, then this would help to measure the performance and use of the infrastructure and space. However, the design and execution of controlled experiments of pedestrian and vehicle negotiations in a real environment are limited by practical and ethical issues about the safety of participants involved in the study (Gorrini et al., 2016). An important example of controlled experiments for pedestrian observations is PAMELA facility that makes it possible to test pedestrian accessibility and other questions within transport system (Childs et al., 2008). Such resources, and its successor PEARL, were beyond the scope of this PhD.

In this study, the aim was exploring the question of how to design and experiment with the idea of dynamic street intervention. Therefore, I choose to use prior observation in a real environment and feed these observations into the simulation in order to further analyse the observation data. This process aimed to result in a design of a tool to iterate and reflect on the initial idea of the dynamic street intervention. Controlled experiments that test the interventions with real participants are left to future research to pursue.

Analysing the Data: Video recordings can provide both quantitative and qualitative data. The dominant tradition in pedestrian behaviour analysis encourages focusing on straightforward, environmentally defined responses that can be extracted through measurement tools such as gap acceptance by calculating the pedestrian's distance from the vehicles (Lobjois and Cavallo, 2007), speed of walking (Ye et al., 2012) or trajectory-based analysis (Jiang et al., 2015). These carefully automated measures provide an important replication basis through quantifying the behaviours. They contribute towards improving the scientific status and precision of the collected data. However, to address the complex nature of pedestrian behaviours, there is also a need to understand the qualitative aspects of their behaviours as they can bring insight on the relationship between data that quantitative analysis found or on variations of pedestrian behaviours by exploring individual cases (Mars et al., 2016).

A particular reason for choosing a qualitative approach is its ability to depict the characteristics of individual behaviours in the environment. This allows us to describe the naturally occurring events in collected data with rich detail (Yang and Gilbert, 2008). This rich data can help us to understand the impact of the local ecology of objects, tools on behaviours and technologies (Heath et al., 2010) rather than deliver deductive laws about universal behaviours. In this research, I have chosen a qualitative approach to understand the particularities of behaviours in the selected environment. This aimed to identify contextual information and the behaviours driven from them to understand the cognitive process of pedestrians.

Understanding the relationship between the contextual information and individual activities is defined as "causation" by Yang and Gilbert (2008). This entails discovering correlations between variables and causal mechanisms by investigating the intermediate steps between the initial positions and final actions. Through looking at the initial, intermediate and final steps, qualitative analysis emphasizes the temporal or time-varying changes by asking how and why things change. This questioning brings the contextual and behavioural processes together by constructing the actors and re-constructing their worlds.

By exploring the temporal distribution of behaviours and contextual processes, qualitative analysis can make clear where, when, how, and for what, the quantitative data can be used and why it matters (Yang and Gilbert, 2008). This characteristic of qualitative observational data is also mentioned as a way to construct and convey quantitative data by Hillnhütter (2021).

Hence, the use of qualitative analysis can improve quantifiable data through providing an explanatory context for it.

I have chosen qualitative analysis in this study to consider how navigation and negotiation through the street is dependent on how individuals make sense of the surroundings through their actions in momentary situations. Understanding relevant particularities of the different situations where people act towards, use and manipulate objects constitutes the social setting of the street scenes is an aspect of qualitative observations that helps to make sense of the activity at hand. Video-based qualitative study can also help to reconstruct the immediate ecology constituted through the interplay between various elements such as behavioural sequences of individuals, contextual information, the relationship between them and temporal distribution. The visible and material virtue of video observation provides the practical and methodological resources to analyse subtleties of social actions produced by pedestrians and others.

A potential limitation is that observations do not provide every aspect of walking in both types of analysis. They carry visual indicators concerning, for example, who walks and for what apparent reason, but these are derived from rough estimations and assumptions about the individual (Hillnhütter, 2021). In this research, indicators about an individual's age, clothes, demographics remained insignificant and were not included in the analysis. Instead, I focused on other kinds of differentiation such as propensity towards risk-taking.

In relation to this, another important aspect of qualitative observational study is the confirmation bias of the observer. This can be explained as the tendency of researchers to see what they are expecting to see when conducting observational study (Marsh and Hanlon, 2007). In their research, Marsh and Hanlon (2007) conducted two studies (including 186 people) and found that when different expectations are given to different observer groups, their observations are biased 'only to a small or moderate degree'. Peters (2020) explains that "insignificant" differences occur when the study subject is a non-social matter. This relates directly to the discussion by Nickerson (1998) of how, when one has a personal stake in the outcome, the level of bias in the interpretation of evidence increases. When a person is not personally involved in the subject, it is difficult to be sure from the findings in the literature whether the person treats the evidence in an unbiased manner or with a small degree of bias, but there must be some concerns related to objectivity and the researcher's assumptions. These fears help explain why researchers sought to increase the scientific validity and reliability of their work through focusing on responses that can be measured and processed within a few well-defined paradigms (Timberlake and Silva, 1994). However, Timberlake and Silva (1994) also mentions that an isolated measure without the regard of its form and function in the contextual basis reveals little insight into systems or mechanisms. Therefore, even though systematic qualitative observation needs careful decisions about how to interpret data (Weiss et al., 1989), it can help understanding the sequence of events, cycles and episodes that shapes the action of individuals.

In the literature, qualitative analysis of observational data about pedestrians is explored through various methods. One example is classification of pedestrians through their purpose in the environment. For example, Mehta (2006) classified pedestrian activities as stationary, sustained and lingering. These definitions define the general potential aim of pedestrians on being in the street space. In a qualitative study of pedestrian-vehicle interactions, Kaparias et al. (2015) focused on directional changes, speed variations, or vehicle acceleration to identify how spatial change impacts on pedestrians and vehicles' confidence and tolerance. Similarly, Alsaleh et al. (2020) investigated the collision avoidance behaviours of pedestrians when they interact with cyclists; they have studied trajectories, directions and speeds of road users. These examples illustrate how pedestrian reactions may be analysed in different circumstances and for different purposes. These authors are, however, more interested in single measures or single-behaviours of interactions than their procedural aspects.

Although, as mentioned, different disciplines (e.g., transportation engineering, traffic psychology, safety science) have empirically studied pedestrian behaviours and interactions, the attempts towards understanding their behavioural and interactional processes during their crossing period are lacking in the literature. Therefore, in this research, I aimed to extract the sequential nature of behaviours where one action follows another in response to the context. To explore this aspect of pedestrian behaviours, I follow a qualitative analysis where I extract data by defining pedestrians actions through complex conceptual frameworks portrayed in the audiovisual data. This kind of "multivariate" extraction requires analysing behavioural and interactional structures and developing a framework to comprehend and represent the social complexity, dynamics and temporal patterns (Whitehead, 1997). Qualitative analysis aims to understand these behavioural indicators, the context that affords pedestrian behaviours, and the pedestrian responses to these contexts. In this research, the understanding of video recordings is gained through interaction analysis whilst the representation of this information will follow two processes: (1) visualisations of the interaction analysis and (2) development of the agent-based modelling.

Creating a Space for Experimentation; An Agent-Based Modelling Approach

This study addresses the questions of *how to experiment* and *how to design* through first bringing the outcomes of qualitative observational analysis into simulation and then creating a space to experiment and try out design interventions. This is achieved through using agent-based modelling which follows the steps of translating the data into an agent-based model, creating the model and iteratively analysing the model. Through this process two things are aimed for: (1) further understanding of the collected data through externalising its analysis in a visible form and (2) creating a space to implement and experiment interventions which impacts on the iterative process of design. In this way, this process first serves as a way to progress in research by defining the problem through refining my understanding of the data. Second, it creates a visual interface to gain insights and reflect on interventions. In this section, I will introduce the agent-based modelling, discuss the appropriateness of the method, its limitations and its application process in this research.

<u>Agent-Based Modelling:</u> Agent-based modelling (ABM) is a tool that includes agents who are autonomous individual elements with properties and actions (Crooks and Heppenstall, 2012). ABM is a suitable toolset for (1) understanding how population behaviour emerges from individual behaviour and interactions (Macy and Flache, 2009); (2) testing, refining and extending existing theories that have proved to be difficult to formulate and evaluate using standard tools (Axelrod and Tesfatsion, 2006); (3) identifying individual heterogeneity (Yang and Gilbert, 2008). It implements the behaviour of different agents on micro-level and depicts the resulting macro-level (interactional or systemic level) structures in the system (Axelrod and Tesfatsion, 2006). Micro-level, in the ABM literature, denotes the entities that include individual characteristics and behaviours (Hanappi, 2017). In micro-level, an entity (or an agent) for example might be an ant. Macro-level, on the other hand, represents the behaviour of the whole group or system (Hanappi, 2017), such as an ant colony.

One of the interesting properties of agent-based modelling is that even though agents are dependent on a set of rules, they have the ability to show complex behavioural patterns (Crooks et al., 2019, pp.10-12). These rules can produce emergent behaviours which can be unpredictable. One of the most known examples of this feature is Conway's Game of Life which shows complex and emergent behaviours based on the three simple rules (which are "If a cell is alive and has two or three live neighbours, then it will stay alive, otherwise it will die. If a cell is dead and has exactly three live neighbours it will change its state to live, i.e. be born.") (Rendell, 2002). However, when we understand how these patterns are formed through documenting carefully, the unpredictability of the model will be reduced.

The set of rules serves a number of roles in agent-based modelling. They describe the dynamical individual behaviours of various agents (Holland, 1992). 'Dynamical individual behaviours' here refers to the different actions or states of agents when interacting with other agents and with their environment. These actions and states can be formed based on internalised social and mental models, internal behavioural rules and cognitive frameworks, formal and informal institutional rules (Janssen, 2005). They are typically derived from published literature, expert knowledge, data analysis or statistical work (Crooks and Heppenstall, 2012). To sum up, the set of rules guide the behaviour, decision making of agents and influence their interactions (Crooks et al., 2019, p.18).

When modelling agents such as pedestrians, unlike cellular automata, their behaviours do not only rely on internal dynamics but also the dynamics of interacting with a complex and changing world (Steels, 1995). To be able to understand and act in the environment, agents' behaviours are dependent on a set of units (or building blocks) such as sensors, actuators and networks. These work together, interact with structures, processes in the environment, resulting in a particular behaviour. These same units may also be involved in other behaviours as well. Coupling the state of the environment and the states of the agents displays the particular behaviour under observation. This focus on the interaction between agents and the world introduces the emergence of complexity (Steels, 1995). Therefore, Wilensky and Rand (2015, p.xvii) argue that agent-based modelling brings a more natural way of describing complexity of systems.

Whilst agents can produce different behaviours as a result of their internal mechanisms and the environment they are in, they also can have different characteristics, as representatives of the population being modelled. Through these characteristics, modellers incorporate heterogeneity into the population (Crooks et al., 2019, p.16). Heterogeneity of agents is particularly useful in the context of representing pedestrians as their behaviours are rarely homogenous. Therefore, understanding and recreating these behaviours are valuable in order to experiment and understand the processes behind them. In this research, I use my video observations to extract typical representatives from the pedestrian population. By identifying these representatives, the aim is to incorporate various pedestrian dynamics into the agent-based model in order to capture spatial and temporal variations among pedestrian behaviours.

One of the main reasons to use ABM in this research is its ability to be manipulable and flexible when experimenting to answer certain questions or generate insights. This manipulable feature of ABM allows for experimentation by implementing new ‘what if’ scenarios that we want to test (Van Dyke Parunak et al., 1998). Furthermore, according to Van Dyke Parunak et al. (1998), these ‘what-if’ scenarios we experiment with in order to improve the system under observation can be easily translated into practice by defining the changes. This aspect of ABM is considered in this study through its ability to show a space in which many sorts of variables, actors, and activities occur autonomously while being connected. Therefore, the model can be used as an open-ended experiment environment in which the relationships between actors serve as indicators to facilitate the development of ideas.

Depending on the purpose and intention of the modeller, agent-based modelling should have an appropriate level of detail (Bonabeau, 2002). However, it might be tempting to incorporate more detail in a model in order to depict the nuances of disciplinary expertise. Modelling in increased detail is especially evident when the model aims to represent what is already known rather than when the focus is on the research question and the model’s goal (Badham et al., 2018). When the level of detail is more than necessary, the model might have too many constraints and become overly complicated (Crooks and Heppenstall, 2012) or it can obscure the relationship between agent and system behaviours (Badham et al., 2018). Therefore, modellers should be selective, including only the details of the real world that are relevant to the purpose of the model. This means that when modelling human behaviours, for example, modellers should include a number of clearly defined aspects of behaviour that they believe have a strong influence on the system under consideration (Crooks et al., 2019, p.94). I approach the level of detail in ABM by focusing on the crossing behaviours of pedestrians by identifying their behavioural process, the dynamics they are affected by and the decisions they make through their actions. These aimed to identify what kind of risks pedestrians can be involved in and how to improve their level of safety without compromising their flexibility of movement.

While clear definition of behaviours is a challenging task for all ABMs, it can be particularly difficult when modelling human behaviour as there is little theoretical agreement on the subject (Crooks et al., 2019, p.174). This can be particularly problematic when estimating the impact of a proposed intervention on human behaviour which is generated by the model rules. For example, in route choice, the question can be how much a person is likely to prefer street A to street B. This agent-centric process-driven perspective of ABMs might require the mechanisms to be specified even when they are not fully understood (Badham et al., 2018). However, this does not mean making arbitrary assumptions about the behaviour and decision-making processes. Instead, one should ground and test each piece of the model against real-world and introduce additional levels of complexity only when it is needed (Farmer and Foley, 2009). I aimed to establish this type of relationship between reality and model in my PhD through building a reflective process between the video observation and agent-based model.

By building the model based on the related aspects with the model's purpose, ABM provides a 'coarse-grained' representation of the real world to understand and represent complex systems. However, this should not mean that the represented system provides holistic solutions (Kikuchi et al., 2002). Since ABM is based on local knowledge and represents a part of a complex system, the ABM should be considered with its limitations and used to receive insights about the systems or ideas that are planned to test. Bernhardt (2007) explains this aspect as seeing the model as a tool to explore system dynamics by building an understanding of when and where to intervene in the system.

In this study, ABM aims to use the existing pedestrian patterns in the street that are gathered through qualitative observational analysis (Chapter 5) to evaluate the design intervention (Chapter 7). In that sense, the ABM leads *forward* towards the trialling of the interventions. The interactions of agents are dependent on the set of rules that are based on the framework created in Chapter 5. By translating these frameworks, the ABM deepens the understanding of relationship between the agents and improves the analysed data by pointing out the missing data in the analysed interactions. The ABM helps to address the complexity of pedestrian interactions at the street level in a systematic way. So, in addition to leading forward to the interventions, the ABM also leads *back* into refinement of the observation.

Designing an Intervention

Through this study, *Designing an Intervention,* I address *how to design* part of the research question by intervening into the street space to create pedestrian-centric street mobility. This section aimed to demonstrate as a way to explore ideas and assumptions about pedestrian-centric interventions. This exploration was conducted by using the experiment space created is described in Chapter 6.

Designers use interventions as a way to approach a current situation or phenomenon to induce change (Chakrabarti, 2009). This is the approach of designers described by Simon (1969, p.55) in his dictum that "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones". Similarly, Schön (1983, p.147) mentions experiments can be conducted in a number of ways such as "exploratory" experiments where the action is taken in order to see what follows, "move-testing" experiments in which the action is undertaken in order to achieve intended change and "hypothesis testing" experiments where multiple hypothesis are compared with observations to identify the correct one. My research aligns with the first two experiment typologies explained by Schön.

In the context of this study, the *design intervention* aimed to address the dynamics, interactions and pedestrian-centricity of street mobility. The idea of intervening into the street with a dynamic approach aimed to be experimented with in an exploratory manner. Therefore, this study consists of experimenting with an intervention and building scenarios in relation to the intervention in order to show the dynamic between the intervention, pedestrians and vehicles.

Through this study, the aim is to show an illustrative example and its development process by using the ABM simulation. By using this exploratory tool, I intend to gain insight about the intervention as part of my broader project of questioning the current narrative of street mobility and explore the interconnected effects of intervening in the street space. My questioning of current street mobility is based on my study of the literature (see Chapters 1 and 2) and illustrates my approach to investigating pedestrian-centric street mobility in order to prioritise their safety and convenience. My objective in exploring ways to incorporate interventions in the street space is to concentrate on the initial experimentation process. Therefore, the simulation tool is intended primarily for early-stage exploration of ideas within the overall project to redesign streets with pedestrian-centric approach. This exploration approach seeks to offer a safe environment to investigate the opportunities of various technologies and address potential insecurities before implementation.

Returning to the ideas of Research through Design, this study serves as a way to progress research by using the simulation tool I have developed. Implementing the intervention in a virtual environment helps in problem- and question-framing and in reflecting on the relations between different actors such as pedestrians and vehicles. This shows the relationship between the idea and the context by visualising the creative process. In fact, simulation in this study serves as a way to visualise a different way of approaching the street by creating a complex and structured platform capable of sustaining many autonomous but connected agents and activities. By doing so it opens the experimental practice for the dynamic intervention planning and helps to navigate around the requirements for designing these interventions. Steffen (2012) states that the experimental practice marks the intersection of theory and practice by implying theoretical considerations and showing a design activity.

As Niedderer (2004, p.29) describes it, “Design becomes here an activity of experimentally joining mental and physical levels of the phenomenon under investigation”. The merging between mental and physical levels is related to making and doing in order to illustrate ideas that are aimed to change or offer a different approach to the current situation. The “making and doing” in this phrase is undertaken in order “to make observations, generate or test hypotheses and to answer research questions” (Steffen, 2012, p. 1757).

Similarly, Evans (2015) refers to this physicality as tangible form and mentions another aspect of visual exploration: communicating the ideas. These visual manifestations help in both conceptualising and communicating ideas by depicting the “insular activity of synthesis” (Kolko, 2010) or, in other words, reflection on the idea. Moving this idea into experimentation in the simulation space, the visual aspects of practice and reflection can signal the potential uncertainties and assist in identifying intervention’s unpredictable outcomes.

Using this study, I illustrate the process of testing dynamic intervention using the simulation tool in order to reflect, contextualise and visualise. Therefore, the aim is providing an exploratory approach to pedestrian-centric street mobility and use of simulation as a reflective tool rather than a predetermined one.

Framing the Practice: Process of Studies

Each method, represented in my research by a different study, is an attempt to answer the various aspects of exploring designing a dynamic pedestrian-centric street mobility in an iterative fashion. First, by identifying the interaction between different elements using video analysis, I have been able to refine what constitutes pedestrian dynamics during their crossing moment. Second, the findings of observational inquiry are fed into the design of the simulation model, which serves as an insight tool for designers.

These two studies were designed as an interconnected and reflective process. Building the simulation model piece by piece entailed revisiting the video recordings and analysis at the end of each modelling phase in order to verify and improve the model. This reflective and iterative portion of my practice improved my grasp of the pedestrian behavioural process and how to represent it. Therefore, one of the unique approaches involved in this PhD is how simulation is designed and how these studies’ confluence can be formed through an iterative process.

The third study provides insights into a potential intervention to street mobility in order to aid designers and other researchers during their initial design and reflection processes. This is intended to be accomplished by using the simulation tool developed through systematic exploration of pedestrian interactions and behaviours in the real street environment. This process again is planned as a reflective one that focuses on how to improve the design ideas for pedestrian-centric street mobility by using a simulation tool. Consequently, reflections and insights were intended to act as feedback mechanisms, steering the design idea into a more plausible and desired version of the initial version.

The relationship between the studies shown in Figure 4.1. Here, through the diagram, I aimed to represent what kind of relationships occurred through the use of discussed methods. For example, the relationships between video recordings and simulation tools influenced the nature of the research in the way that I moved between the studies and methods in order to understand and work with the dynamics between pedestrians and their surroundings. On the other hand, the relationship between the intervention and the simulation required translating the idea into simulation and gaining insight about this translation.

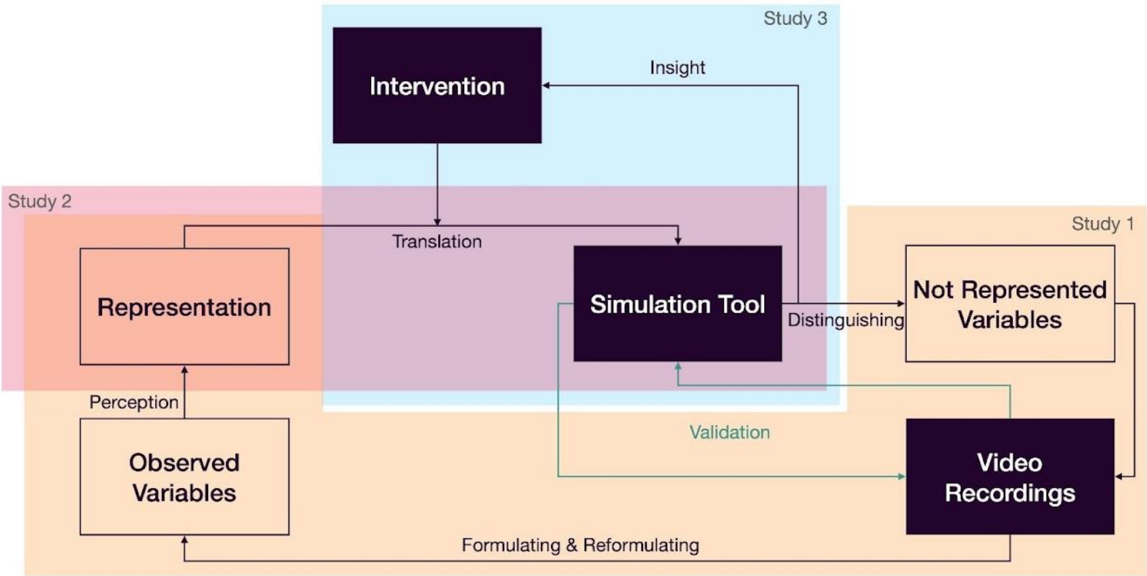


Figure 4.1. Diagram of the Relationship between Methods.

The following three chapters demonstrate how the discussed methods are used, respectively. In the next chapter, I employ video recording data to conduct a qualitative observational study to analyse how pedestrian behaviours are formed spatially and temporally. Then, I investigate how to recreate these observations in the simulation platform by constructing a pedestrian agent-based model and discussing the translation process between two studies. The following chapter demonstrates the use of simulation when an intervention is implemented.

Chapter 5 Understanding the Context through Conducting a Qualitative Observational Study

The aim of this practice is to address the question of how to design a pedestrian-centric street system that manages street mobility. The objective of the following studies is to design a framework which incorporates a dynamic feature to the street by introducing responsive interventions. A responsive street intervention shapes the street by understanding its agents, the pedestrians. This understanding is achieved by incorporating a level of awareness about pedestrians into the intervention. In this study, the aim is to understand pedestrian behaviours and interactions in order to represent them through simulation where the intervention will be performed.

The practice begins by asking, "What behaviour occurs in the real world and what influences pedestrian behaviours?". The answer to this question is explored by studying a selected area through observing and interpreting the pedestrians' behaviours, their interactions and the street environment they are embedded in. This part of my research is based on data collection through on-site video recordings, photography and desk research about safety perception measures. This study starts with a literature review about previous pedestrian studies which used video recordings and then explains the data collection and analysis processes.

Introduction

The majority of collisions that occur between pedestrians and motorised vehicles are on the street where the two modes interact with each other (Schoon, 2010). Therefore, street environments must be appropriately designed to provide safety with a preferred level of service for pedestrians. In order to answer critical questions related to safety and safety perception of pedestrians, there is a need to understand the current street conditions, pedestrian interactions, components and processes. To design and assess pedestrian-related systems, it is important to have a good understanding of pedestrian behaviour.

Pedestrian behaviours have been divided into three categories: strategic, tactical and operational behaviour (Daamen and Netherlands Research School for Transport, 2004; Hoogendoorn and Bovy, 2004; Kielar and Borrmann, 2016). This division is made through a hierarchical classification of their decisions made during their journey. Strategic behaviour includes destination choice and activity planning such as choice of transportation, departure time and planned arrival time (Ishaque and Noland, 2008). At the tactical level, the route selection, navigation and scheduling are included. The operational level includes microscopic behaviours during the journey such as next visible navigation node, walking path and interactions with other pedestrians, built environment and vehicles along the way (Kielar and Borrmann, 2016). Although a number of studies have focused on pedestrian behaviour, the heterogeneity of microscopic pedestrian behaviour compositions has been overlooked and the analysis was generally made to achieve statistical or mathematical models.

By contrast, in my research, the objective is to explore the different pedestrian behaviours by looking into how these behaviours are sequenced and how pedestrians operate in the street. For this purpose, I conducted an observational study to identify the manifested risk-taking behaviours and safety perceptions related cues which served a basis for the construction and design of the agents in the simulation. The aim of this study is to identify the potential stimuli for pedestrians to take small to high risks in the environment and the other measures related to their safety (explained further in the following section). While these analyses helped to create the pedestrian agents in the simulations, they also provided insight for potential design interventions by creating a better understanding of the pedestrian crossing behaviours and their context.

The purpose of this study is to investigate operational level pedestrian behaviours through a series of video observations in the selected environment in London. The data on operational pedestrian behaviour such as part of their routes, route choice and interaction with the built environment, other pedestrians and vehicles are collected through video recordings. The goals of this study are to observe and identify different types of pedestrians, understand the characteristics of their interactions and walking behaviours through examining their route choice and how they act in crossing moments. The objectives of this study include:

- Collecting and analysing operational pedestrian behaviours.
- Providing qualitative analysis to compare between different pedestrian behaviours, sequences and characteristics.
- Analysing pedestrian interactions involving other individuals or elements from the built environment.
- Establishing a working framework to describe different types of pedestrians on observed street areas to transfer the analysis to the simulation.

In this study, particular emphasis has been placed on analysing individual pedestrians. In Section 2, I synthesize the information that came out from the literature about pedestrians' safety, safety perception and risk-taking behaviours and how they have previously been investigated. In order to understand the relation of different parameters with pedestrians' safety, safety perception and risk-taking behaviours, a description of parameters and how they can be assessed is provided. The purpose of Section 2 was to provide the description of parameters and show how the processes, structures and function of street components can be analysed and evaluated through field and desk research.

In Section 3, I describe the data collection method and the area of study. Video observations were conducted at Battersea Park Corner near a controlled crossing area and pavements. In this section, the detailed analysis of the area includes land use map, network analysis, pavement capacity, connectivity, conflict points, qualities of the pavements, amenities in the area and qualities of the crossing. The analysis was made through mapping of the area, photographing and site visits.

Section 4 describes the aim of the data analysis. Then, in Section 5, the data analysis process is explained, starting from preliminary data analysis through using spreadsheets and then the process of deeper analysis of individuals using interaction analysis. In the deeper analysis, pedestrian behaviours and interactions are recorded through transcribing their behaviours, interactions and their situational context.

Section 6 structures the data analysis through visualisations for a more meaningful presentation of the acquired information. Following the data transcript, this part aims to clearly demonstrate the pedestrian interactions and behaviours through three types of visualisations. These are trajectory mapping, behavioural sequence analysis and feedback loops. These visualisation techniques are one of the contributions of this thesis by clarifying the data extracted from the video recordings. The aim of the visualisations is (1) showing the spatial relationship of pedestrians through trajectory mapping, (2) demonstrating the context and events' relationship with pedestrians' behaviours with behavioural sequence, and (3) showing the situational conditions when they are crossing through feedback loops.

The subsequent section describes the results. Through the discussion, I group the different pedestrians and propose a framework for each pedestrian group's characteristics. These frameworks aim to show the general working principles of the pedestrian behaviours while enabling a degree of heterogeneity to create different types of reactions. These reaction types include different types of behaviours for different situations.

The findings of the video analysis contribute to shaping pedestrian agents in the simulations, as well as providing valuable insights of their own. The pedestrian frameworks were revisited during the simulation stage and provided more input such as identifying the behaviours to avoid vehicles. Through improving pedestrian simulation, this study contributes to creating a tool to understand and design for pedestrian behaviours so that the "decision-makers", professionals and users (pedestrians) can have an area where they can discuss and see the implications of the design decisions.

This study is descriptive and correlational and follows a qualitative approach. It, therefore, does not deal with the quantity or frequency of particular pedestrian actions, but instead focuses on their interpretation and their potential causes.

Literature Review

Methods Used to Understand Pedestrian Behaviours in Literature

Pedestrian behaviour studies have been conducted in various ways. This chapter summarises the various methods used to analyse the pedestrian behaviours and why video observation techniques were chosen in this study.

The aim of this pedestrian study was to collect data for creating a basis for the pedestrian agent design for the simulation through allowing new understanding of what pedestrians do and how they negotiate in the street. For simulation purposes, there are a number of ways to collect data about pedestrians. Some tools and techniques used by previous studies are:

- Data collection through Telecom (Grignard et al., 2018)
- Data Collection through Microsoft Kinect Sensor (Seer et al., 2014)
- Data Collection Through Open Trajectory Dataset (Lovreglio et al., 2017)
- Video Feed Scene Analysis (Crooks et al., 2015)
- Video Observation (Feliciani et al., 2017; Gorrini et al., 2018)

Other methods which have been used to analyse the risk-taking behaviour and safety perception of pedestrians includes questionnaires (Granié, 2009; Nordfjærn and Şimşekoğlu, 2013; Papadimitriou et al., 2013), field survey and recording of crossing behaviours in different conditions (Papadimitriou et al., 2016), video survey (Raghuram Kadali and Vedagiri, 2020), combined video graphic survey/questionnaire (Ravishankar and Nair, 2018), setting an experiment and interviewing (Cœugnet et al., 2019), interviewing and VR simulation experiments (Deb et al., 2017) and video recording of the areas (Gitelman et al., 2019; Khatoon et al., 2013).

The previously mentioned tools and techniques can be categorized as tools to reach what is "really" happening and tools to achieve a "re-construction" of what happened. There are a variety of different tools to use to reach a data-related re-construction of events such as interviews. These re-constructions tend to transform and decrease the reality of the events by importing the meaning and perspective of the re-constructor (Bergmann, 1985; Jordan and Henderson, 1995). In the event of collecting data from a re-constructor (e.g. through an interview about an event), the interpretation of data is handled as primary data (Bergmann, 1985). According to the aim of any particular research, the bias of the re-constructor can be useful; however, the researcher should keep in mind that they do not have a chance to reverse the process from construction to reconstruction of the event. As the events themselves have already disappeared, what is accepted as data is in reality the recollection of the event by the teller (or re-constructor). All the data from interviews to non-recorded field observations fall into the category of re-construction (Jordan and Henderson, 1995).

In this research, I have used video observation to gain an understanding of pedestrian behaviours and create a framework for pedestrian agents in the simulation. Video offers ideal data when researchers are interested in what "really" is happening (presented) instead of the explanation or re-presentation of what happened. Video recording produces a high level of detail of what is happening which can't really be reached by explanation or description of the event. It also offers permanent access to the primary record of the event. This makes it available to repeat and review the event an unlimited number of times and change the temporal measures of it through increasing or decreasing the number of frames per second. It also captures the details and the bodily behaviours and movements which are not portrayed in the description of events.

In video recordings, the bias of the re-constructor is transferred to the bias of the machine (Jordan and Henderson, 1995). The machine's capabilities, position, vision and viewpoint are some of the bias examples in video evidence. Video observations are constrained by the limitations of the technology. However, this constraint(bias) is consistent during the data collection.

Video Observation Parameters of Pedestrian Behaviours in Literature

The literature on Parameters related to Pedestrian Safety

This section looks at some of the studies made throughout the literature to study pedestrian behaviours and parameters related to their safety. Within safety, pedestrian behaviours arising from pedestrians' apparent perception of their own safety are included. According to Eller and Frey (2019), perceived safety is connected with perception of structure, predictability and the individual's confidence. By focusing on safety, I aim to explore the individual variations of pedestrian actions in different situations of conflict.

In this section therefore, I analyse the previous literature on pedestrian video observations, particularly focusing on pedestrian safety perception. I divided the parameters into two main categories which are environmental conditions and situational conditions.

Below (Table 5.1) shows the parameters for environmental conditions. Environmental Conditions are divided into two sections: location factors and physical characteristics. Table 5.1 shows the parameters in each section, which literature they are derived from and how they are addressed in the next section of this video observation study. The parameters for situational conditions are described in Table 5.2. These are divided into three sections which are the volume in the environment, interactions and behavioural conditions. This table also includes data about their literature and how it is addressed in the following account of my study.

Environmental Conditions

Category		Factors	Reference	Methods of Measurement
Location Factors		Land Use	Dixon, 1996; Petrisch et al., 2005; Oakes et al., 2007; Anciaes & Jones, 2016; Kadali & Vedagar, 2015	Assessed from open street mapping tool (Digimap) and geographic information system tool (QGIS)
		Network Analysis	Petrisch et al., 2005	Assessed through QGIS
		Connectivity	Gallin,2001; Shay et al 2006	Assessed through Digimap data
		Conflict Points	Gallin, 2001; Petrisch et al., 2005; Olszewski et al 2016	Assessed through site visits and mapping tools
Physical Characteristics	*The Quality of Sidewalk:*	Sidewalk Space / Sidewalk Capacity / Sidewalk Ratio	Fruin, 1971; Turner et al., 2006; Dixon, 1996; Petrisch et al., 2005; Landis et al., 2001	Measured from plans or during site visits and showed the area through colour
		Presence of Street Parking	Landis et al., 2001	Assessed through site visits and mapping tools
		Buffer or Barrier from the Travel Line / Cycling Lane	Turner et al., 2006; Landis et al., 2001	Assessed through the photographs taken during the site visit
		Sidewalk Surface Quality/ Curbing Quality	Gallin, 2001; Turner et al., 2006	Assessed through the photographs taken during site visits
		Minimum Width	Turner et al., 2006	Assessed on site visits
		Amenities	Dixon, 1996; Landis et al., 2001	Assessed through the photographs taken during site visits
		Approach to Sidewalk	Turner et al., 2006	Assessed through site visit and mapping tools
	The Quality of Crossing:	Length of Crossing / Number of Lanes / Crosswalk Capacity	Department of Transport, 1995; Landis et al., 2001; Petritsch, et al., 2005	Assessed through the photos taken during site visits
		Legibility of Crossing; Dropped Curbs Texture and Colour	Turner et al., 2006; Petritsch et al.,2005	Assesed through the photos taken during site visits
		Obstructions ; Permanent (poles, signs, chairs etc) or Temporary (bin, vehicles etc) and Sight Distance	Department of Transport, 1995 ; Gallin, 2001; Turner et al., 2006	Assessed through the photos taken during site visits
		Active Signal (Amenities)	Department of Transport, 1995 ; Petrisch et al., 2005	Assessed through the photos taken during site visits
		Given Crossing Period	Department of Transport, 1995	Assessed through video

Table 5.1. Measurements of factors affecting pedestrian safety (environmental conditions).

Measurements of Factors Affecting Pedestrian Safety Perception
Situational Conditions

Category	Factors	Reference	Methods of Measurement
Volume in the Environment	Vehicle Volume on the selected road	Petritsch et al., 2005; Landis et al., 2001; Dixon, 1996	Assessed by counting the number of vehicles over 15 min. on video recordings.
	Pedestrian Volume on the selected area	Gallin, 2001	Assessed by counting the number of pedestrians 15 min. on video recordings.
	Mix of Path Users	Gallin, 2001	Estimation of different users
	Presence of Pedest-rian in each frame	Landis et al., 2001	The number of pedestrian in each journey (max. and min.)
	Presence of Vehicle in Each Frame	Kaparias et al., 2012	The number of vehicle in each journey (max. and min.)
	Speed of the Vehicle	Landis et al., 2001	Travel Time of the Vehicle
	Speed of Pedestrians	Olszewski et al., 2016	Travel Time of the Pedestrian
Interactions	Classification of the Pedestrian & Vehicle Encounter	Olszewski et al., 2016	Vehicle and Pedestrian Behaviours when they encounter on the video
	Perceived Conclicts	Petritsch et al., 2005	The Number of Traffic Interruptions for each journey
	Perceived Exposure	Petritsch et al., 2005	Analysing the location of the individual (crossing distance)
	Crossing as a Group	Ge, Collings & Ruback, 2012	Identifying the groups
	Delay (Signal Delays)	Petritsch et al., 2005; Gallin, 2001	Assessing the video timings
Behavioural Conditions	Individual Interaction Maps	Ge, Collings & Ruback, 2012	Creating maps for each indi-vidual about their interactions including the timings
	Personal Spaces	Ge, Collings & Ruback, 2012	Finding their minimum dis-tance to their surroundings on the video
	Directions	Petritsch et al., 2005	Following the direction of their head on the video
	Trajectory of Ped.	Olszewski et al., 2016	Following their path on video
	Trajectory of Vehicle	Olszewski et al., 2016	Following their path on video
	Speed of Vehicle	Petritsch et al., 2005; Landis et al., 2001	Assessing acceleration and deceleration through video
	Speed of Pedestrian	Olszewski et al., 2016; Ge, Collins & Ruback, 2012	Assessing acceleration and deceleration through video
	Potential and Actual Vehicle Conflicts	Petritsch et al., 2005	Counting the number of vehicle conflicts in the video
	Individual Crossing Time	Department of Transport, 1995	Timing individuals crossing on the video
	Collective Behaviour	Ge, Collings & Ruback, 2012	Finding the relation between individuals by grouping them

Table 5.2. Measurements of factors affecting pedestrian safety (situational conditions).

Literature in Risk-Taking Behaviour

One of the primary tasks that pedestrians perform when they need to cross the road is to check the environment and identify best conditions to cross (Cœugnet et al., 2019). This decision-making process of pedestrians is characterised by Cœugnet et al. (2019) as an adaptive system that is dependent on their use of chosen strategies, although in some cases, this decision making may lack strategy or thought process. Therefore, in most studies (e.g. Khatoon et al., 2013; Madigan et al., 2019; Raghuram Kadali and Vedagiri, 2020) the process of pedestrian decision making in crossing is represented through gap acceptance. Gap acceptance is the available time between the pedestrian and the oncoming vehicle that the pedestrian considers sufficient or safe before crossing (Cœugnet et al., 2019). It establishes a metric to help analyse the decision-making process of pedestrians.

The factors that affect gap acceptance are explored by a number of researchers. For example, Khatoon et al. (2013) studied the effects of vehicle type and waiting time on gap acceptance. Whilst the vehicle type did not have much impact on gap acceptance of pedestrians, the increased waiting time of pedestrians changed their gap acceptance. When the pedestrian's waiting is increased the accepted gap distance is reduced. Another study by Raghuram Kadali and Vedagiri (2020) explored the correlation between the number of lanes and gap acceptance. Through their study, they found that the vehicular gap size, frequency of attempt to cross, pedestrian rolling behaviour and type of vehicle played an important role. Vehicular gap, in this study, refers to the distance between two vehicles, one after each other. The pedestrian rolling behaviour indicates their crossing behaviour between the vehicular gaps instead of waiting for larger gap acceptances.

Risk-taking behaviours are reported to be affected by increases in vehicle flow (Leden, 2002) and increases in the number of lanes (Raghuram Kadali and Vedagiri, 2020). In addition to the vehicle and environment related aspects, the individual risk-taking behaviour also derives from the pedestrian's individual abilities (Ishaque and Noland, 2008), experience and awareness (Cœugnet et al., 2019). According to these individual variables, the non-risky behaviour occurs when pedestrians correctly assess the distance and speed of the vehicle, when they interact with the vehicle (e.g. confirming each other's potential actions through gazing), and understanding the road situation by waiting (e.g. hesitating pedestrians who cross the street when there are no vehicles and through waiting readjust their waiting time, crossing at a safe distance and speed) (Cœugnet et al., 2019). According to Cœugnet et al. (2019) risky behaviours of pedestrians can be dependent on five factors: (1) an assessment bias of the situation (e.g. mistakes during evaluation, poor visibility) (2) social influence on individual's behaviours (e.g.

following the pedestrian flow), (3) being distracted (e.g. focusing on an event occurred at pavement instead of vehicles on the road), (4) a habit of breaking rules, and (5) time pressure.

The behavioural changes between risky behaviours and non-risky behaviours were another aspect summarised by Cœugnet et al. (2019). Whilst risk-taking behaviours were less perceptive and had less waiting time hence, fewer head movements, non-risky behaviours occurred when pedestrians verified the situations around them numerous times and increased their perceptive activity. These behaviours suggest that pedestrians often make trade-offs between delaying their crossing, speeding their crossing, or taking risks during their crossing periods (Ishaque and Noland, 2008).

Summary

In the first part of this section, I explained what other methods are used to analyse pedestrian behaviours and then I explained the reasons for choosing video recordings to collect data and outlined the benefits and drawbacks of this method. I subsequently looked into the previous research undertaken through video analysis on pedestrian behaviours.

A variety of parameters related to pedestrian behaviour are taken into consideration in the literature. These helped me to examine what parameters should be considered and which ones show fundamental importance for the pedestrian modelling approach. Some of the parameters which can be important for the model are pedestrian speed (Collins et al., 2012; Olszewski et al., 2016), pedestrian and vehicle conflict resolutions (Olszewski et al., 2016), exposure (Petritsch et al., 2005), conflicts (Petritsch et al., 2005), pedestrian gap acceptance while crossing the road (Pawar and Patil, 2015), vehicle (Kaparias et al., 2012) and pedestrian (Landis et al., 2001) presence in the crossing moments, trajectories (Olszewski et al., 2016), connectivity (Gallin, 2001; Shay et al., 2006) and conflict points (Gallin, 2001; Olszewski et al., 2016; Petritsch et al., 2005).

While these parameters were valuable to identify in the literature, I also aimed to create a heterogeneous pedestrian agent population by assigning different values that could exemplify types of individuals with varied behavioural tendencies. The variations between agents, in the literature, often occurs through defining individual variables such as speed, gap acceptance or directions. In my research, through this study, I aimed to make use of the findings from the video observation to identify the perception and action loops and their potential relations with the individual's surroundings. The heterogeneity in my research is therefore primarily concerned with individuals whose behavioural patterns differ from one another.

Unlike most previous studies, I used the video study to build behavioural sequences which shows the sequential relationships between the pedestrian's actions and its context. This approach as a result, helped to shape the agent's framework in the simulation, while the parameters are used to create different characteristics amongst the pedestrians who share the same behavioural framework. For example, my concern when identifying the behavioural frameworks was looking into pedestrian actions such as crossing, and mapping what could be the trigger of this behaviour.

Data Collection

Selection of Data Collection Method

The data required for the development of the model calibration and validation include both the site-specific characteristics and the behavioural dynamics of pedestrians and vehicles.
The site-specific characteristics can be easily obtained through maps, field research etc.
The collection of dynamics of pedestrians and vehicles is more challenging. Existing research on microscopic pedestrian behaviour suggests the following possible approaches to obtain this type of data:

- Video camera recording with automatic video image processing software.
- Video Camera recording with manual data extraction.
- Radar or laser speed gun
- Instrumented vehicle: A vehicle equipped with multiple cameras, sensors and computers for observing pedestrians as well as the very detailed dynamics of the vehicle and the driver can be obtained over a long period of time or distance with relatively high accuracy.

The aim of my data collection was to draw a picture of the pedestrian behaviours by looking at their behaviour sequences, interactions and their relation to the street environment and other road users. The capture of these data was intended to inform qualitative understanding of individuals and their relationships. The video recordings were obtained in six (6) sessions between March 2019 and May 2019 with a total length of 3 hours.

The method of video camera recording with manual extraction is selected in this research to collect and extract all necessary information which makes it a time-consuming process. This partially affected the decision on collecting appropriate amounts of data from the street. The amount of data arguably may not be enough to draw definitive conclusions of a particular site's usage, users and temporal changes from a quantitative perspective. In addition, the video recordings could have covered different types of sites which would have brought more insights. Additionally, the sites could have been examined during other daily, seasonal periods to provide a more comparative study that could have demonstrated temporal differences which are not covered here.

As noted previously, another aspect was the presence of the researcher. This can affect the area of study and the input for the video during the recordings. The recording sessions did sometimes affect the events on the scene, for example, sometimes people were interested in my own stationary activity at the scene. In the next section, I will be examining the study area.

Area of Study

The video recordings were made at Battersea Park Corner, London, in the United Kingdom. This study focused on one intersection in this area. The Battersea area was chosen because of its lack of public transport links (Bayley, 2020). Subjectively, the area appears to be a transitional space where people pass through to arrive somewhere, rather than spending time to enjoy the space. This quality of the space, being transitional, serves the purpose of this research. There are no potential distractions around the crossing area such as monuments or historical buildings etc. In this section, I will give a thorough overview of the area where the observations were carried out and also look particularly at the elements which facilitate or obstruct movement. The following overview was made partially through desk research using the Geographic Information System (through QGIS software) and open stream mapping tools (Digimap, OpenStreetMap and Google Earth), and on-site analysis through photographs.

<u>Land Use:</u> The relationships between land usage and urban travel patterns have been a widely researched topic in the literature (Anciaes and Jones, 2016; Oakes et al., 2007). Use of land can be shown through identifying transport links, shopping areas, parking areas, bus stops, cycling facilities amongst others. (Anciaes and Jones, 2016). According to these points, we can categorize the land use in the following categories; residential, commercial, industrial, business and mixed land use (Kadali and Vedagiri, 2015). It has been shown that land use has a significant impact on pedestrian behaviours, especially in the crossing facilities. The Pedestrian Environment Review System (PERS) shows that footways/footpaths can be generated through

and affected by the land use of an area and therefore transportation links, as well as pedestrian facilities, should be arranged according to the land use or vice versa (Pantzar, 2012).

The image below, Figure 5.1, shows the land use of the focus area in Battersea. Identification of the transport links such as the railway station, bus station, park, shared bicycle docking station and petrol station are highlighted with blue dots. The yellow points show the potential destination or starting points of pedestrian journeys by emphasizing facilities such as schools, shopping areas, and post offices. Through this image, we can generate the connections between the points shown as they can be potential destination points. Land use maps can help to identify the area's purpose and usage while also helps to predict the potential pathways through the potential districts such as transportation points, commercial areas or shopping districts.

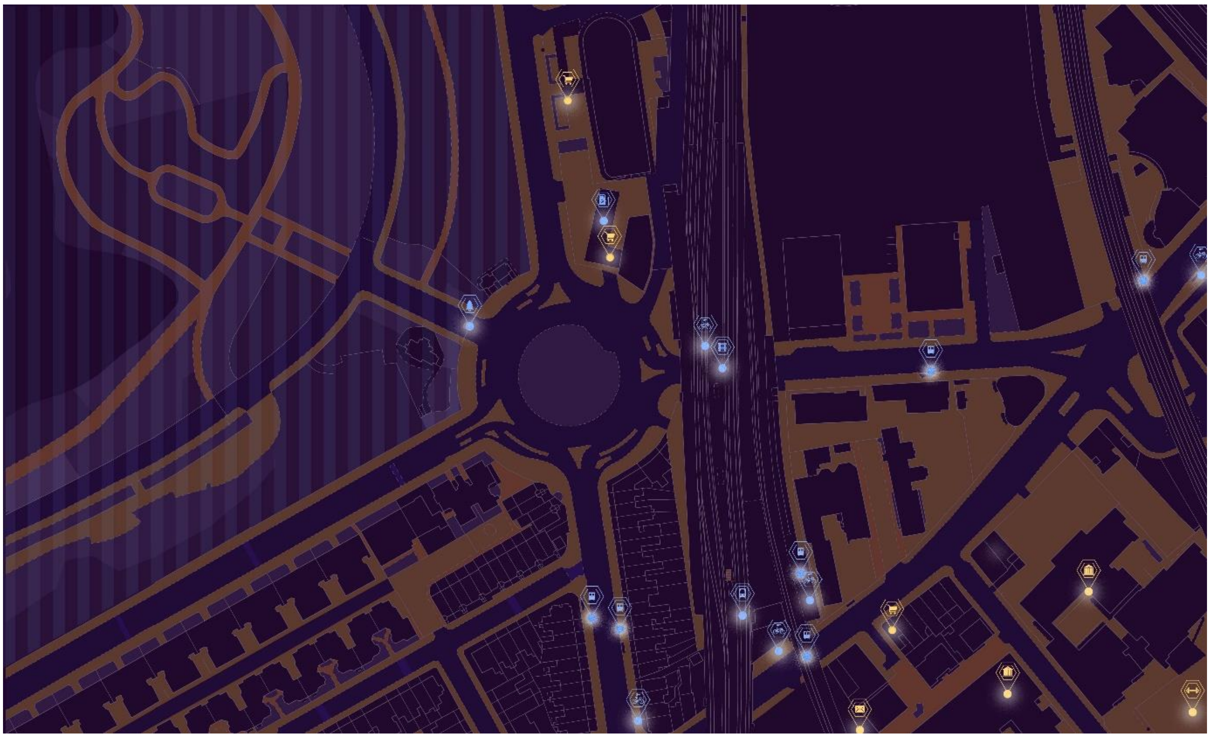


Figure 5.1. Land Use Map. Image generated through geographical data (Digimap & QGIS), graphic overlay (Adobe Illustrator). Showing the potential destinations of pedestrians such as shops, transportation links and schools.

<u>Network Analysis:</u> Network analysis shows the potential pedestrian paths responding to the land development forms mentioned in the previous section (Ozbil et al., 2011). The focus of network analysis is to explore street patterns and forms and their relation with the potential pedestrian paths. For example, it can show strategic routes for pedestrians such as areas which have fewer crossings or the shortest path to arrive at a certain destination, or trip predictions that are associated with transit access (Petritsch et al., 2005).

The following map (Figure 5.2) shows frequently selected paths in the area according to the Global Positioning System (GPS) data acquired through the OpenStreetMap (OSM) which is publicly available map data.

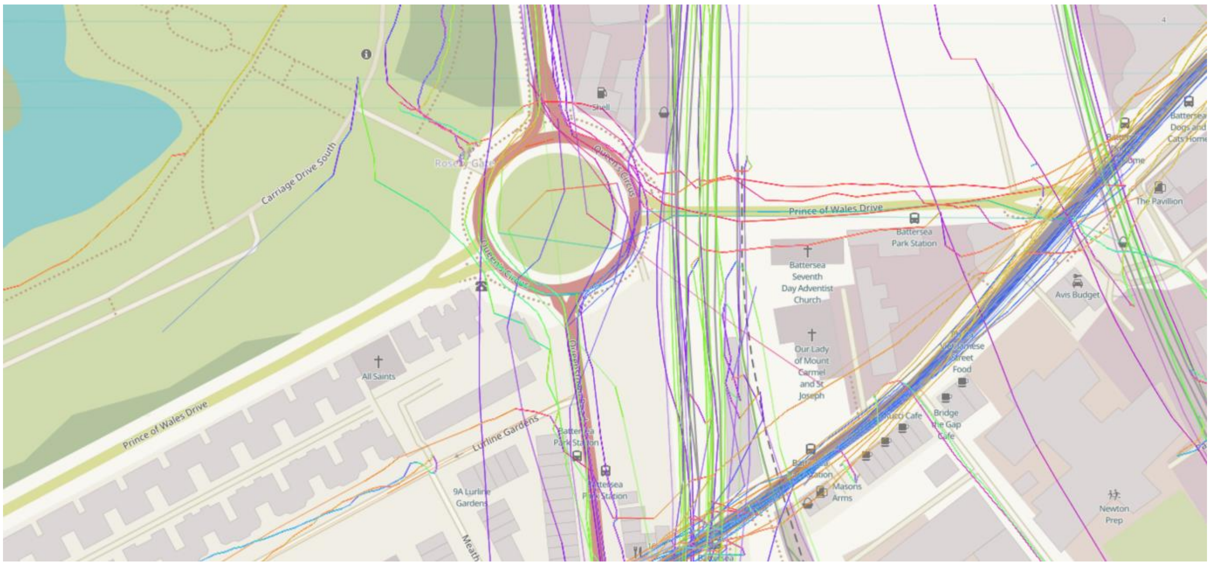


Figure 5.2. Network Analysis Map (openstreetmap, 2020).
Showing the pedestrian routes and their relation with the space.

<u>Area of Focus:</u> This part looks more closely into the area where the video recordings were made. I wanted to show several features of the environment: *pavement capacity*, *connectivity of the pedestrian path and conflict points.* The pavement capacity measure was developed by Fruin (1971) to evaluate the walking space and pavement width dedicated to pedestrians. In the following map (Figure 5.3), based on Fruin's work, the pavement capacity measure of the area is shown by colouring the available spaces for pedestrians in purple. This technique is also helpful to see the scale of the pedestrian-dedicated environment compared to others as well as showing the connectivity and interruption points within the pavement network. Throughout the thesis I will often refer to these interruption points as conflict points (as explained further in the Glossary). These points are helpful to assess the connectivity of the pavement. Shay et al. (2006) mention the effect of the pavement's connectivity on pedestrian behaviours. Connected pavements mean that there is a useful, logical and direct link between the key points (Gallin, 2001). The conflict points which interrupt the pavement connectivity are shown with orange dots. We can see that the junction is full of conflict points. These points can also help to assess the approach to the pavement, which means how many points are located around each controlled or uncontrolled crossing (Turner et al., 2006). In this area, we can see two conflict points next to our central focus area which are used mainly for parking which is shown with orange rectangles.

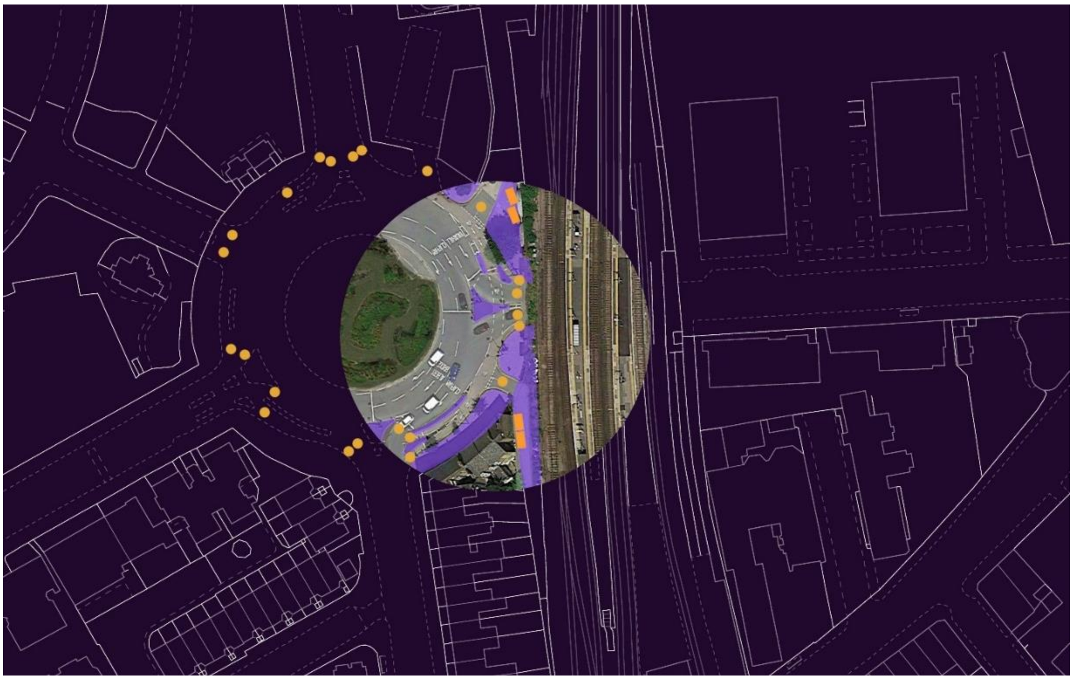


Figure 5.3a. Area of Focus.
Image composed from geographical data (Digimap & QGIS), satellite imagery (Google Earth), graphic overlay (Adobe Illustrator) showing the area where the videos are recorded and identifying areas such as pavements, crossing points and parking spaces.

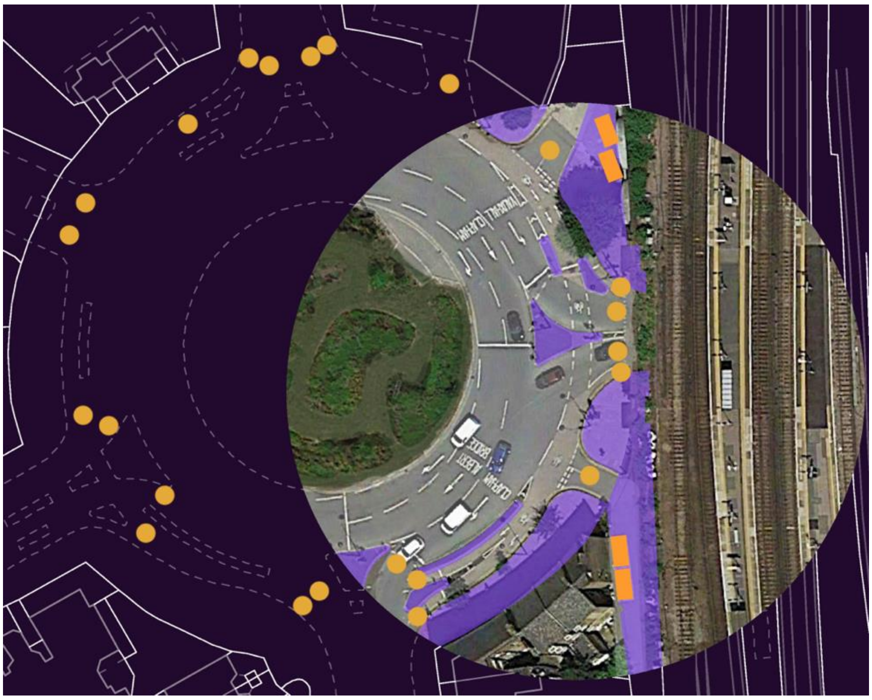


Figure 5.3b. Area of Focus (detail).

Qualities of the Pavement: This section first focuses on the *amenities* at the street environment such as pavements, cycle lanes, traffic lights, central reservations and street trees (Figure 5.4) then goes down to street level perspective to identify on-site *qualities of the pavement* and street environment (Figure 5.5, 5.6 and 5.7).

The main purpose of Figure 5.4 is to show the key elements of the street. The image emphasises the pedestrian space with light purple colour, cycle lane with light blue colour, motorised vehicle space with dark purple and street trees with green layovers. The wider rectangular shape shows the crossing areas that have two traffic lights, two push buttons and a central reservation area (indicated with circular images). The smaller rectangular shape marks the shared bicycle docking station.

On the crossing, there were no medians or pedestrian refuges, while there was a sign for vehicles and a barrier for vehicles a little further off from the crossing to split and manage the vehicular movement. Next to the crossing, under the bridge, there was also a bicycle docking station which can be an interaction point during the pedestrian's journey. There were no pedestrian-scale amenities such as street furniture or benches but there were a few trees around the pedestrian area.

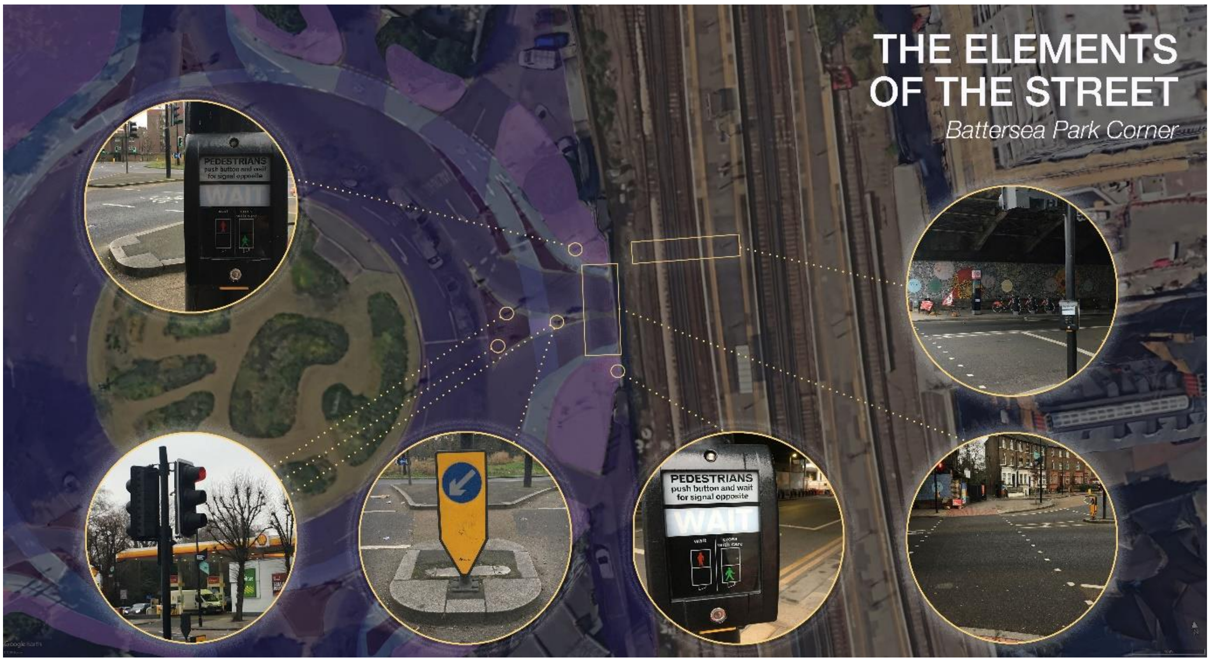


Figure 5.4. The Amenities at the Street.
Image composed from satellite imagery (Google Earth), graphic overlay (Adobe Photoshop). Illustrating the pedestrian, vehicle and cycling spaces and infrastructure.

In Figure 5.5, we can see the street environment from the street level. This street-level analysis shows the general qualities of the pavement such as pavement surface or crossing area and emphasizes the location of certain elements such as barriers, traffic lights, crossing buttons and obstructions.

The bicycle lane was used as a buffered space between the carriageway and the pavement. The pavements were as usual slightly raised above the motor-vehicle and cycling area. In the literature, this is also categorized as a barrier (Landis et al., 2001). Apart from the elevation and the bicycle lane, there was no lateral separation element between pedestrians and motor traffic. There were a few temporary obstructions on the pavement such as outdated pedestrian warning signs (one of them can be seen in the light purple rectangular shape in Figure 5.5). There was also a railway bridge next to the crossing area which can be seen from the image. The surface quality of the pavement was continuous, smooth and I did not observe any unbalanced or uneven kerbs with cracks.

Figure 5.5. Pavement Qualities.
Showing the infrastructure, dedicated spaces such as crossing area, cycle lane and other qualities of the environment.

The minimum width of the pavement measured 190cm (Figure 5.6) between the shared bicycle docking station and the wall of the bridge (Figure 5.7).

Figure 5.6. The Minimum Width of The Pavement. *Figure 5.7. Shared Bicycle Docking Station.*

<u>Qualities of Crossing:</u> The crossing is of the Pelican type, which means that it is a pedestrian light controlled crossing which includes a push button as an active signage system. The crossing extends over a total of 2 motor vehicle lanes and 2 bicycle lanes. There is no pedestrian refuge.

Figure 5.8. Qualities of Crossing. Showing the number of lanes, crossing area and driveway.

The legibility of the crossing is increased, particularly for those with deficient vision, through the tactile patterned surface, which is the area coloured yellow in Figure 5.8. As can be seen from the image, the connection between the crossing and pavement is made by dropped kerbs. There is no lateral separation from the road such as railing, and there are no road humps. However, on both sides, there were outdated signs for pedestrians which can be classified as a temporary obstruction. Under the bridge, on the pavement, there is a shared bicycle docking station (Figure 5.7) which can be classified as a permanent obstruction. Other permanent obstructions are traffic lights on the pavement. There is also an open parking area which is an unmarked crossing point close to the intersection.

Aim of Data Analysis

Unlike the other types of video analysis methods which have been used to provide data for simulations, in this research as previously explained, the video analysis was qualitative rather than quantitative. To understand different aspects of pedestrian behaviours, I have used various techniques such as observational coding and interaction analysis and developed a series of visualisations. For the purposes of rigour, I will mention observational coding briefly in this research as during the analysis process I have not found it sufficient to extract subtleties of behaviours. Then I will discuss the use of mapping interaction analysis and visualisation techniques in order to understand and present the pedestrian behaviours and their context.

At the beginning of this study, I was planning to use an ***observational coding*** sheet to analyse the video recordings. Observational coding is a tool to analyse and record the behaviours as they occur (Pesch and Lumeng, 2017). It is used for to analyse how frequent a behaviour is occurring. The coding sheet tracks the parameters in the protocol in the video. In observational coding, the coding system can give binary or categorical variables. The reason to use observational coding was to evaluate the video recordings systematically according to the parameters found in the literature (Pesch and Lumeng, 2017). While this technique is useful to provide a systematic and even statistical analysis, it was not able to represent the multidimensional nature of the interactions and the feedbacks or interaction loops during the behaviours. In other words, it was not able to contextualize the observations in terms of spatial and temporal relationships of pedestrian behaviours. That is why I decided to use observational coding only to categorize the individuals according to their interactions for *preliminary data analysis and clean up*. These categorizations helped to identify which pedestrian journeys should be looked into detail and the differences between them. Then, I investigated a method that can give explanations and coherence to the flow of contextualised events and behaviours.

Following observational coding, I transcribed the events in the video using a range of techniques derived from the method of *Interaction Analysis*.

Data Analysis Process

This section provides a qualitative analysis of the data derived from video recordings of pedestrians on the street. I have used a variety of techniques to understand the various aspects of pedestrian activity. In each subchapter, I present the tools I used and explain how I applied them. The following section includes a preliminary analysis of the video before moving on to the interaction analysis method and how it is used. The final section discusses how I have used visualisations to structure the data derived from interaction analysis.

Preliminary Data Analysis and Clean-up

Preliminary data analysis helps identify pedestrians' initial characteristics and general properties of the dataset by inspecting the raw video recording data. While this process provides an overview of the video recording data, it also helps identify unstable, irrelevant, and incomplete parts and improve the data quality. In this research, by improving data quality, I mean distinguishing irrelevant observations that do not fit the specific problem this research aims to explore (e.g., excluding unrelated agents, such as a pedestrian waiting around the corner for a vehicle to pick him up), as well as removing parts of the data that are not usable because they are not clearly observable (e.g. too distant). On a few occasions, the data proved to be only partly accessible because of the movements occurring during the camera placement. In these instances, I analysed the available portion of the data while stating the inaccessible parts during the interaction analysis.

Initial structuring of the video data was conducted through a coding sheet on Google Spreadsheet by analysing and documenting a number of parameters. The coding spreadsheet helped to keep track of the events in the video. The parameters are formed by asking questions with binary (yes/no) or short descriptive responses. This form of preliminary data organisation helped me in the systematic use of raw data by identifying where to look while interaction analysis is in process. To define the data related to pedestrians' journeys and characteristics, I prepared a set of questions to be answered for each pedestrian. These questions are:

1. What is the timeframe of the pedestrian's journey in the video?
2. What are the recognisable characteristics of the pedestrian?
3. Was the pedestrian walking alone or with a group of pedestrians?

4. Is there any overlap of the pedestrian's path with any section of the road or pedestrian crossing?
5. If the pedestrian crossed a road or a crossing, what colour was the light during this part of their journey?
6. Was the pedestrian multitasking, e.g., using a phone while walking?
7. What was the act through which the pedestrian showed their intention to cross?

These questions are formed through the field observations before conducting fine-grained sequential analysis through interaction analysis. The first question is entered into the interaction analysis to explain the temporal unfolding of the interaction by using reference to the video time code. This made it easier to locate the referred video fragments. The second question was helpful to understand which pedestrian was the focus of observation during the stated time frame. The third question aimed to understand whether the pedestrian was in a group or not and the fourth question explored whether the pedestrian crossed the road. As a result of these questions, I identified each pedestrian who crossed the road – whether or not at a pedestrian crossing – in the video recording. The last three questions acted as reminders for the next stage of interaction analysis study to give preliminary information about their risk-taking and attention levels.

In the next section, I will be looking into each pedestrian's activity to give more context and explanations to the observed actions. This contextualisation will be made by looking into spatial and temporal variables while they are performing their behaviours as well as the sequence of their actions.

Interaction Analysis

Interaction analysis is an interdisciplinary method to explore individuals' interactions between themselves and their surroundings (Jordan and Henderson, 1995). It consists of content listings, transcription, identifying the ethnographic chunks, segmentation, temporal organisation of the activity, participation structures, and the activity's spatial organisation. Data extraction creates data points by identifying interaction hot spots, separating behavioural events via determining their beginnings and ends. It analyses how individuals announce the end of the interaction, examines their gestures, movements, nonverbal behaviours, errors in their interactions, producing a task analysis and temporal data such as rhythms, high and low points of the interaction.

In this research, I am only concerned with what individuals appear to perceive and express, and others react to, rather than with any deeper interpretation of what people are perceiving, thinking and feeling which can sometimes be different and more complex than what they express visibly or verbally. Therefore, the perception refers, here, to the information seemed to be driven through the perceptual system of an individual and its influences on their actions. I am particularly interested in understanding the situational context where the individual receives information and the subsequent actions performed by the individual. My aim is to explore the process of interaction through the visual cues represented in the environment through behaviours.

To further on this point, when I refer to pedestrian perception, choice, or other internal mechanisms that are not technically visible in the analysis, I do not imply their internal mechanisms. Instead, I observe their actions and analyse what they appear to be doing. It was beyond the scope of this study to investigate what pedestrians were 'really' sensing and thinking, as that would create another PhD. I only had the visual evidence in front of me and my own interpretation of what pedestrians perceived, noticed, or observed. When describing my observations of what pedestrians were doing, I sometimes use expressions like 'when pedestrian A observed a vehicle on the crossing'. These kinds of expressions were a short way of saying 'appeared to observe' and should always be understood in that sense.

I used interaction analysis when transcribing the events in the video recordings as it incorporates a variety of data since it captures multiple aspects such as space, time and individuals. Capturing people’s response in real space and time in the street context and analysing their interactions qualitatively by considering these dimensions differentiates my research from previous examples that use automated and quantitative measures (Beitel et al., 2018; Ismail et al., 2010), semi-automatic video analysis to detect and determine trajectories (Olszewski et al., 2016), marking and counting pre-determined measures such as vehicle yielding, distance of yielding and trapped pedestrians (Hua et al., 2009). In these studies, researchers focused on the actions that pedestrians perform in a more quantitative manner by counting and marking the occurrence of certain behaviours. By using interaction analysis, I aimed to understand the process of interactions and behaviours occurring in the environment by looking into nonverbal behaviours of pedestrians, how pedestrians react to the inputs from their surroundings and what are the patterns. Some considerations included where pedestrians are looking, what is happening in that area, and whether or not they act based on their perception.

Other qualitative studies of pedestrians have focused on semi-structured interviews (Faas et al., 2020) and telephone questionnaires (Allsopp et al., 2007). In interaction analysis, gestures, gaze and material objects are as important as language and unlike language they have visible materiality (Norris, 2004). In my study, I examine through interaction analysis this visible materiality that the video recordings provide, and make no attempt to capture pedestrians' explanations or interpretations of their own actions.

In aiming to understand and describe what is going on in a given interaction, and analyse what individuals express and react to in specific situations, I occasionally take notes on what possibly is the intention of the pedestrian. Still, it is important to acknowledge that the one and same action can have different meanings, intentional or unintentional. When analysing the pedestrian interactions, my main concerns include two aspects of the individual's characteristics: (1) expressions of apparent perceptions, thoughts and feelings; and (2) the different attention/awareness levels. These aspects are based on the observations on what are actions pedestrians perform, what kinds of inputs they receive and how they react. These observations are crucial when translating the video analysis into the pedestrian agent creation process for simulations. While the expressions and behaviours help to build the pedestrian's operational behaviours, the attention/awareness levels can help me to build the tactical level of pedestrian agents.

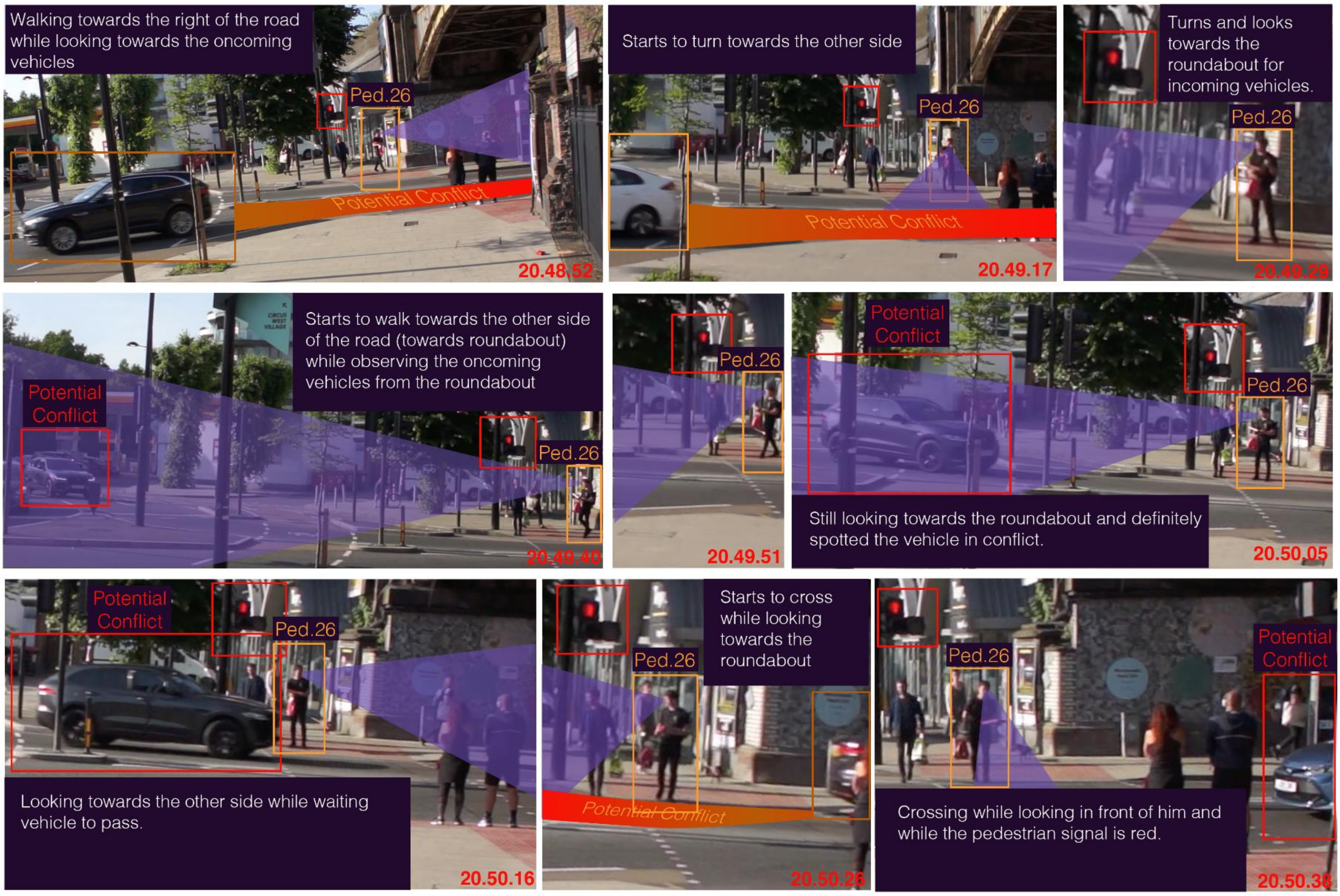


Figure 5.9. The Transcription Process of Pedestrian Behaviours.
The Representation of Transcription Process for a pedestrian through the Frames from the Video.

Following the preliminary study, content listing was the first technique used. I created a summary of the events and behaviours appearing in the video. This summary helped to create a brief overview of the data gathered. Following this, I expanded the content listing through more detailed transcription (Figure 5.9). Translation of visual recording of events into written transcripts requires reduction, interpretation and representation in order to create meaningful information. These requirements are decided often based on what the researcher is interested in and their backgrounds (Bailey, 2008). In this research, my aim is to explore pedestrian's behavioural data specifically during their crossing period. Therefore, I have focused through my written transcription on representing the pedestrian's behavioural and interactional data in spatial and temporal dimensions.

The extended version of the content listing included pedestrians' body movements, gestures, interactions, nonverbal behaviours, object manipulation (such as pressing the pedestrian button), use of certain products (earphones, headphones, phones etc.), and other notable behaviours such as communicating with the person next to them. For extended content listing the answers for the following questions proved useful:

1. What actions did the pedestrian perform?
2. Did the pedestrian observe other pedestrians around them or seem to be influenced by them?
3. Did the pedestrian look for vehicles around them?
4. Did other vehicles or pedestrians' movements around the pedestrian seem to affect the action the pedestrian performed? If so, how is it affected?
5. Did the pedestrian pay attention to the traffic light?

The behaviours were transcribed chronologically allowing both sequence and duration to be captured. This helped reveal causal sequences as well as the durations of pedestrians' journey, crossing time, waiting time, and vehicle observing time. These temporal measures helped to identify the agent's priorities in the further stages. To explain the relationship between the pedestrian and their surroundings, I decided to include details about the pedestrian's surroundings in these transcripts. Vehicle detail, for example, is added to demonstrate possible conflicts along the pedestrian's path. The spatial data about pedestrian's surroundings helped to answer the following questions:

1. What was the colour of the traffic light when the pedestrian was crossing?
2. Were there any vehicles around the pedestrian while they were crossing?
3. What events took place during the process of the pedestrian's journey?
4. Were these events changing or stopping the actions performed by the pedestrian?
5. Was there any relation between the pedestrian's actions and spatial changes happening around them?

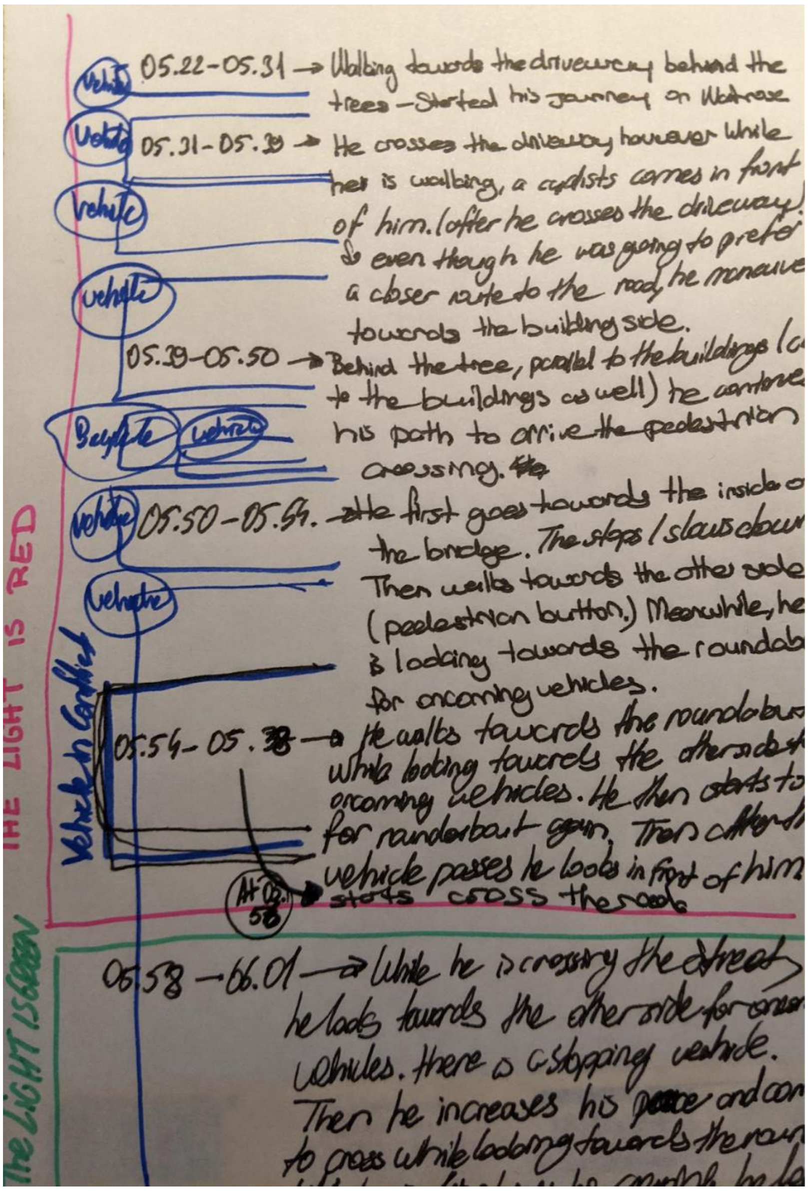


Figure 5.10. Showing the transcription of video data on paper.

While these data points helped to identify the pedestrian behaviours, interactions and their relations with temporal and spatial conditions in the environment, showing these findings using text proved to be extremely messy (Figure 5.10). I decided to structure the data using visualisations to increase clarity and make it easier to search for data. During the visualisation process, I applied other steps from the interaction analysis, such as identifying behavioural processes, each activity's spatial organisation and separation into behavioural units. Three visualisations are produced for each pedestrian. These include trajectory mapping, behavioural sequences and feedback loops. Each is explained in the following section.

Structuring the Data Through Visualisation

Introduction

Following the transcription from the interaction analysis, the next step was to clearly demonstrate the pedestrians' interactions and behaviours specifically for those who crossed the road. Since the data created through interaction analysis was in the form of a written text, it primarily provided descriptive information regarding the pedestrian journey. To illustrate the relationship between pedestrians' behaviour and their context, I first examined each pedestrian's path and created visualisations using trajectory mapping. In parallel to the trajectory mapping, behavioural data is represented by behavioural sequences, which display each action taken by pedestrians and their situational context. Via feedback loops, I aim to demonstrate the situational context which the pedestrians are in during the crossing period. Through these tools, this section aims to illustrate the causality of pedestrian behaviours rather than their quantity or frequency.

Trajectory Map

I used trajectory mapping to illustrate correlations between the pedestrian's actions and the environment. Since a pedestrian's route selection is often motivated by environmental factors, I addressed the activity's spatial organisation by visualising maps and pedestrian routes. Trajectory maps represent details about each pedestrian's journey. Specifically, the maps demonstrate the routes pedestrians chose, the condition of the traffic light as they crossed, whether any vehicles were present during their journey, and if so, the path vehicles took. This mapping technique depicts an overview of pedestrians' journey and their relationship with their environment. The trajectory map helped contextualise the behavioural sequences by defining the spatial conditions during the agent's activities and the agent's route selection based on these conditions.

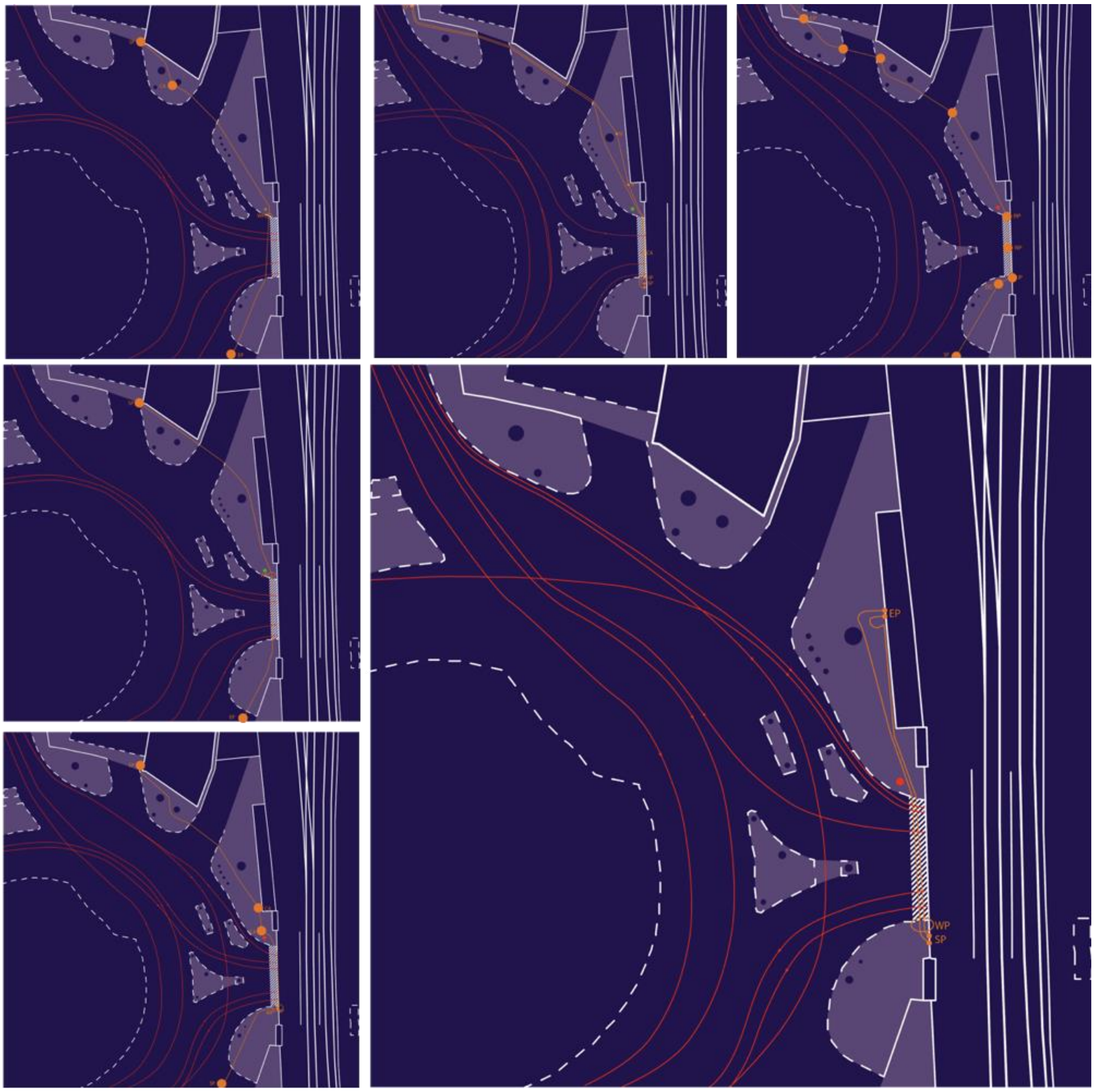


Figure 5.11. Trajectory Maps of Pedestrians' Journeys at Queen's Circus, Battersea, London. The maps are generated based on the OpenMap data and visualised by using QGIS and Adobe Illustrator software. Data related to obstacles, traffic lights, paths of vehicles and pedestrians is added based on observations from the video recordings.

Figure 5.11 depicts six individual pedestrian journeys that were observed through video recordings. In the illustrations, the environment is depicted through different shades of purple, with the light purple areas representing the pedestrian areas and the dark purple areas representing roads, roundabouts, buildings and the bridge area. Two types of white lines are used to emphasise the layout. Dashed lines are used for road edges, while continuous lines are used for buildings and bridges.

The area marked with a hachure represents a signalised pedestrian crossing from a top view. A red or green dot at the corner of the pedestrian crossing indicates the light's condition when the pedestrian was crossing. The various sizes of purple circles on the pavement indicate that there are obstacles such as trees or lamps in those areas. The red lines on the road area show the vehicles' path during the pedestrian's journey. The orange lines show the path of an individual or a group of pedestrians. The orange dots represent the journey's significant points.

Pairs of letters next to some of the orange dots provide brief information on the pedestrian's path and structures with which they interacted. These are abbreviations for starting point (SP), interaction point (IP), returning to the path (RP), collision avoidance (CA), endpoint (EP), direction change (DC), spatial interest (SI), waiting point (WP). The starting point represents where the pedestrian enters the camera frame. Interaction point refers to the point at which pedestrians used an explicit interaction method to signal their intention to cross (such as a traffic light). Returning to the path implies that the pedestrian has turned back to their original track, which had been deviated from due to a situation on it. Example situations include the presence of obstacles such as other pedestrians or the need to use the pedestrian button. Collision avoidance refers to deviating from a path due to obstacles such as vehicles, physical structures and other pedestrians. The endpoint symbolises where the pedestrian leaves the camera frame. The term 'direction change' stands for the directional changes that occur for a specific reason, such as using a pedestrian button. Spatial interest represents the diversions on the pedestrian's path to get closer to a particular attraction on the street space, such as window-shopping. The term 'waiting point' refers to the location where pedestrians waited to cross the street. The behavioural sequence analysis is provided in the following section to provide more detailed information about pedestrians' interactions with physical structures and other agents.

The trajectory maps were useful in outlining the areas pedestrians occupied during their journey, whether they encountered any obstacles and whether the environment influenced their journey. They allow insights into potential disruptions in the pedestrian's route. When designing the simulation, the trajectory mapping helped to locate potential destination points. It also shows the frequency of paths used by agents such as legal trajectories (crossing only in the designated pedestrian crossing) and free trajectories (desire lines which is discussed on Chapter 2). Each trajectory represents a different strategy for crossing the street. Trajectory mapping shows the different levels of costs or risks built on different value assumptions (Hill, 1984). The visualization of trajectory mapping shows the flow between points, gives an initial idea about the level of risk pedestrians take and how the approaching vehicles, geometric and environmental conditions affect the trajectory. Merging the sequential data with contextual information of the environment gives insights about prior actions by the pedestrians, as well as the features of the environment in which the crossing takes place.

Behavioural Sequences

I established behavioural sequences in order to define pedestrian behaviours and their relationships with the situations in which they occur. This analysis provides a temporal visualisation for each individual to demonstrate their process of behaviours. Behavioural sequences involve multiple lower-level actions. They include behaviours such as gaze, head movement, stepping towards pedestrian crossing. Multiple numbers of lower-level actions form higher-level actions, which can also be called behavioural units. An example of higher-level action is "preparing to cross", which includes lower-level actions like waiting, looking towards oncoming vehicles and pressing a pedestrian button. Additionally, the higher-level actions can be overarching or embedded in another (i.e., preparation to cross is embedded in the crossing period). Even though the higher-level actions are the same in all pedestrians, the lower-level actions vary in each pedestrian journey.

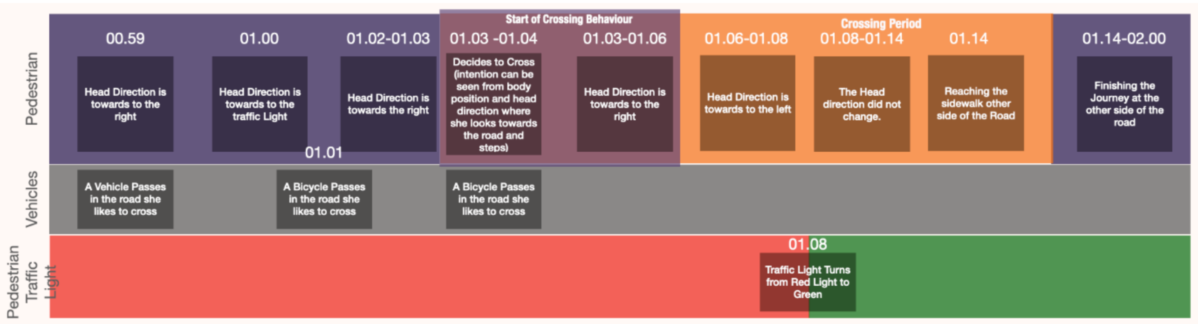


Figure 5.12. Behavioural Sequence Visualisation Outline. The maps generated based on the data extracted from the video recordings through the interaction analysis transcripts. The visualisation has three types of data: (1) pedestrian behaviour data, (2) temporal data, (3) contextual data. Pedestrian behaviour data are represented in two levels: (1) lower-level actions through squares and (2) higher-level actions through colour blocks which include multiple lower-level actions. Temporal data are defined on both lower-level action units and vehicle units. Contextual data includes the vehicle presence and traffic light condition during the pedestrian's journey.

The arrangement of behavioural sequences is based on the transcription of interaction analysis. In the transcription, as mentioned before, there are several data types. Along with the pedestrian's behaviours and actions, the behavioural sequences also include contextual spatial and temporal data. Spatial data is divided into two sections: the vehicle section and the traffic light section. The vehicle segment provides vehicle data on two different paths: the crossing area and the roundabout. Timings are located above each pedestrian action and above each vehicle. The structure of the behavioural sequences is based on the temporal organisation of the activities. Time is zero at the start of each observed sequence and progresses linearly to the right in minutes and seconds.

The behavioural sequence maps represented the relationship between the pedestrians and their surroundings. They are used in the following chapter for simulating pedestrians by contributing the conceptual frameworks for each pedestrian typology. In the next section, I visualised pedestrians' feedback loops during their crossing period to emphasise the inputs pedestrians received during their decision-making process and identify each prevalent input that made them act.

Feedback Loops

Feedback loops describe the interrelationships between the environment and pedestrians. They focus on the negotiation process during the pedestrians' crossing period. The aim of feedback loops is to understand what data pedestrians gathered before they started to cross and the prevalent input that made them act. To represent the flow between pedestrians and their surroundings, I created diagrams for each pedestrian. In general, I have looked into vehicles on the road, traffic light conditions and other pedestrians on the street as resources of input (Figure 5.13). While I have included the static physical structures in the street in Figure 5.13, these were understandably not observed to dynamically modify pedestrian's behaviours during crossing decisions.

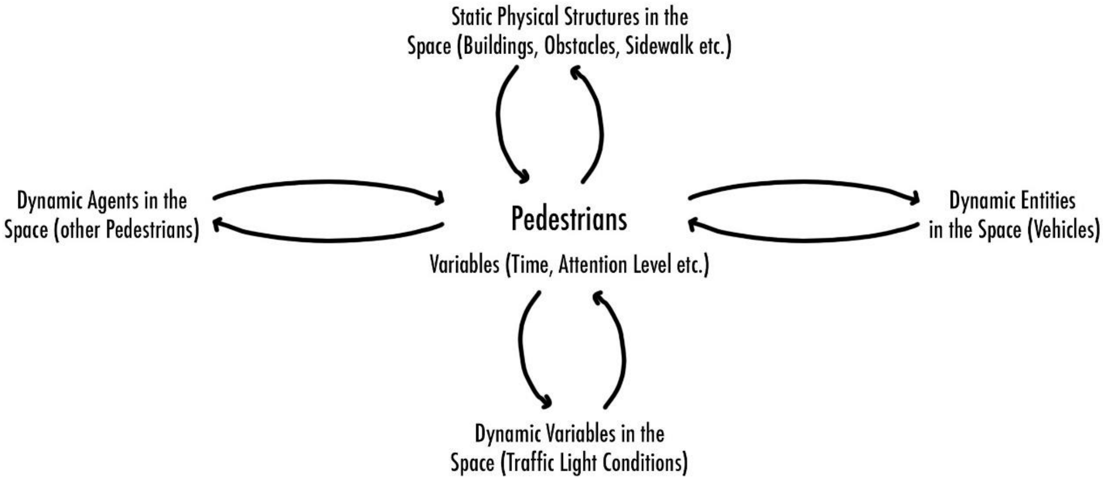


Figure 5.13. General Feedback Loop Visualisation. This visualisation shows what affects a pedestrian's decision to cross the street. In this visualisation, all the potential inputs are shown; however, not every pedestrian feedback loop visualisation includes all the information represented in this figure.

There are also individual variables that can be measured based on the performed behaviour when the pedestrian needs to cross the street. For instance, the value of time for each pedestrian journey and their attention level can show differences. These individual values are identified based on the behaviours that pedestrians performed. For example, multi-tasking or being in a hurry can be considered to represent a lower attention level. On the other hand, taking time to cross the street and looking around for potential conflicts can be considered to show a high attention level.

Feedback loops helped me to identify the priorities given by the pedestrians when they needed to cross the street. Based on the individual pedestrian, the priorities varied between the inputs derived from the situations on the street and their own variables such as time and attention level. Therefore, I looked into each journey to understand what was informing the pedestrian. The following visualisations show different pedestrian processes and emphasise the last input they have received before they have crossed. The last input is determined based on their gaze (direction of their head) before they have crossed the street. In some cases, individuals might also take account of a combination of inputs.

What informs pedestrians is partially dependent on their internal variables. These variables in this research are outlined as time and attention level. Time shows how long pedestrians can spend on their journey. This time variable is generated through looking whether they were getting uncomfortable after waiting on the crossing for a certain time, or were they getting faster or slower. Attention level is based on the time and their distraction level. Their distraction level is measured through whether they were following the environment and whether they were performing other tasks through their journey, such as talking on the phone, listening to music, looking into the phone etc.

At the same time, how pedestrians act on pedestrian crossings is interconnected with the situational context they are in. The situational context is influenced by several dynamic factors. These involve the actions other pedestrians perform, the condition of traffic lights, the location and speed of the vehicles around the crossing. Pedestrians consider these factors according to their variables (time they have or their attention-level). For example, in the first visual of Figure 5.14, the pedestrian had time and decided to cross according to the information coming from the traffic light; they were not observed to be taking action based on the vehicle location and speed or the other pedestrians' actions. On the other hand, in the second visual, the pedestrian was influenced mainly by the other pedestrians' actions. They were aware of the traffic light, but they were not considering it while making the decision to cross. Their attention-level was low because they did not take their time to observe the street, rather they took the decision to cross and observed the traffic while crossing.

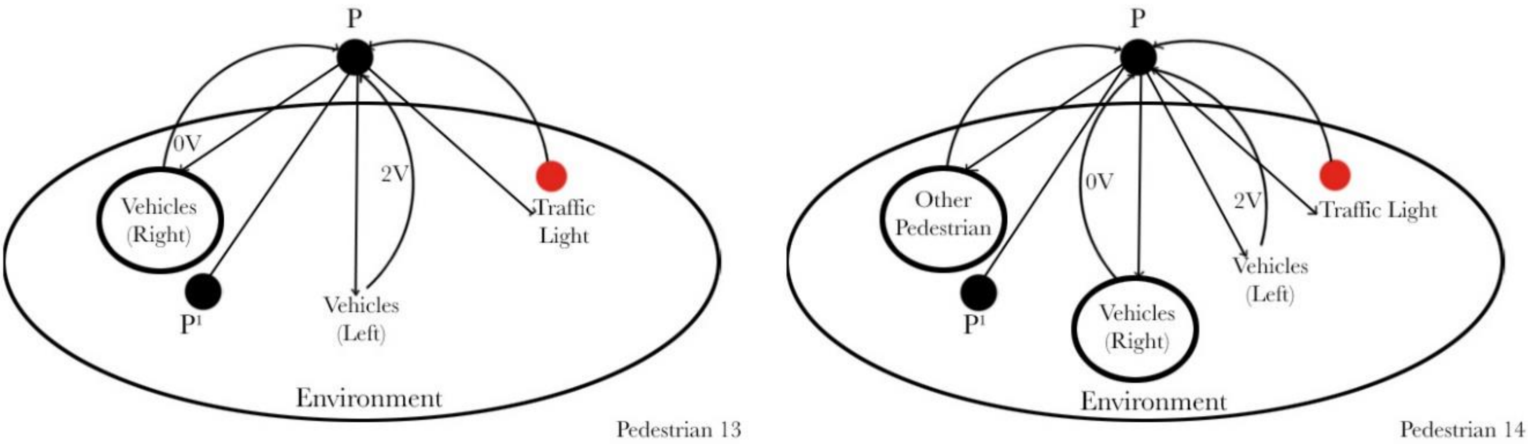


Figure 5.14. Feedback Loop Visualisations for Different Pedestrians. This visualisation demonstrates the different types of feedback pedestrians gather in their journeys. In the visuals, emphasize on the last input marked with a circle around it. P stands for pedestrian and P_1 represents the action performed by the pedestrian. V symbolizes the number of vehicles.

Summary

This section of the review of practice summarised how the data analysis was conducted. The preliminary analysis helped identify the pedestrians who have crossed the road, their temporal positions in the video recordings, and brief information about their behaviours. The following step was to determine the interactions and behaviour performed by pedestrians who crossed the road. Therefore, the interaction analysis technique is applied by transcribing the events and behaviours on the video. This technique was useful to gather descriptive information regarding the pedestrians' journey; however, detecting the correlational relationship between pedestrians' behaviours and their surroundings was challenging as it included a large amount of data. Thus, the last section aimed to identify each pedestrian's timeline, their identifiable attributes and their process of crossing the street. The visualisations included trajectory maps, behavioural sequences and feedback loops of each pedestrian. In the next section, the collected data through these steps is compiled to be used in the simulation.

Structuring the Visualisations of the Simulation: Constructing Pedestrian Typologies and Behavioural Frameworks

Introduction

In "On Constructing A Reality", von Foerster, (2003) shows Pask's visualisation characterising the nervous system's evolution (Figure 5.15). Through this and other visuals, he talks about the neurophysiological explanations for his experiments related to the individual's perception of the environment. I found this simple visual very similar to the process I have been following while transforming reality into simulations throughout this practice.

In the following part, von Foerster, (2003) suggests that "computation" occurs in two levels: (1) the operations which are performed and (2) the organisation of these operations represented through the structure of the nerve network. In the first part of this practice review, I have talked about the operations (in this case, behaviours and interactions) performed by pedestrians on the street. In this part, I will take the first step to look into how the organisation of behaviours can be represented through simulation.

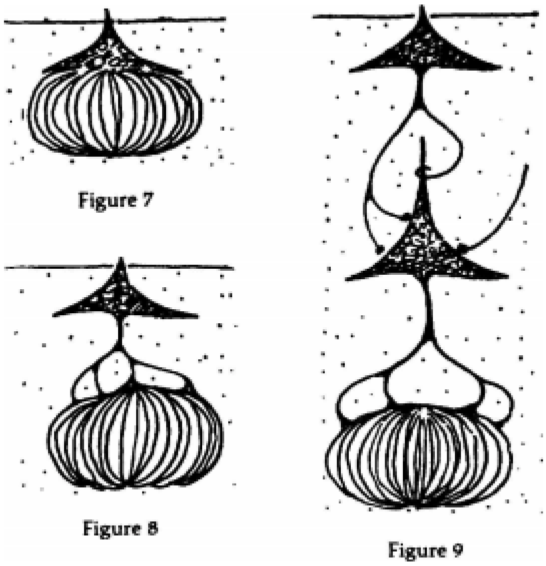


Figure 5.15. Evolution of the Nervous System visualised by Gordon Pask, published in On Constructing A Reality by Heinz von Foerster in 1973.

The following part looks at how the interactions have been captured through the feedback loops and fine-grained behavioural sequence analysis. For each type of interaction, a number of pedestrian analysis samples are given as examples. The first part focuses on constructing pedestrian typologies through examining the feedback loops, which presents the input and output flow through the preparation-to-cross period. In the first part, the pedestrians are grouped according to their prevalent input. I undertook a comparison to identify similar and dissimilar cases according to the features identified in the feedback loops. In the second part, the behavioural sequences from the pedestrian typologies are compared by looking at their associative, similar, differentiating characteristics, their minimal and maximal contrasts. Based on this comparison, the second section attempts to determine patterns in the pedestrian typologies and whether their typologies vary in terms of internal variables or situational occurrence.

Constructing Pedestrian Typologies Based on Data Analysis

My definition of pedestrian typologies was based on pedestrians' decision-making processes as expressed in their observable behaviour. These processes were represented in the previous section through the feedback loops. These feedback loops aimed to show what pedestrians were taking into account while taking decisions and which input was prevalent. The external elements that influence pedestrians are vehicles, the traffic light's condition and other pedestrians (Figure 5.16, 5.17 and 5.18). In the feedback loops, there are four principal types of input that pedestrians look for: (1) vehicles at the right, (2) vehicles at the left, (3) traffic lights and (4) other pedestrians. Which sources of information they look at and what they have considered differs according to their characteristics as agents. Here, I look at each input by describing the common characteristics and differences of each category. This approach aims to give a general picture of pedestrian typologies found in the video data.

The classification was first made between the pedestrians who crossed the street based on the traffic light status and those who did not. For example, in Figure 5.16, pedestrian 24, pedestrian 25, and pedestrian 28 decided to cross the street based on the traffic light's condition. While pedestrian 24 made an explicit interaction by pressing the pedestrian button (PB), pedestrian 25 and pedestrian 28 just waited for the traffic light's condition to turn green. Pedestrian 25 might have decided not to show an explicit interaction because pedestrian 24, whom she was travelling with, already showed it by pressing the pedestrian button. On the other hand, pedestrian 28 was behind other pedestrians crossing the street while waiting and did not see that pedestrian 24 pressed the pedestrian button. From this, it can be understood that pedestrians' behaviour of communicating their intent to cross can be passive and implicit – for example just waiting for the light to turn green – or active and explicit such as by pressing the pedestrian button and waiting for a confirmation. Another difference between pedestrian 24, pedestrian 25 and pedestrian 28 was that while pedestrian 24 and pedestrian 25 were interested in the situational context, such as other pedestrians and vehicles around them, pedestrian 28 was not seen to be paying attention to any place except the crossing area. This situation might occur because pedestrians 24 and 25 spent much more time waiting than pedestrian 28 before crossing the street.

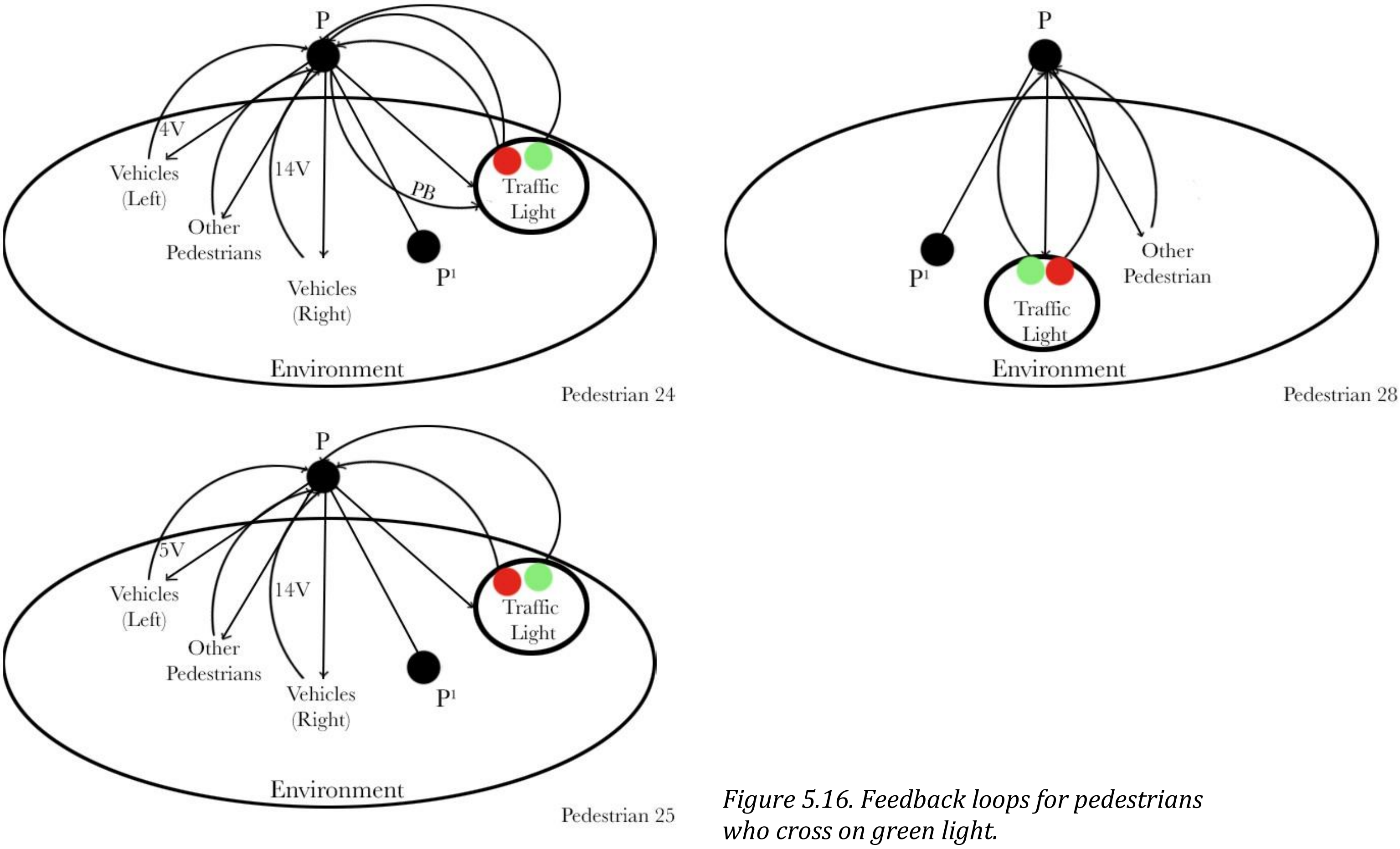
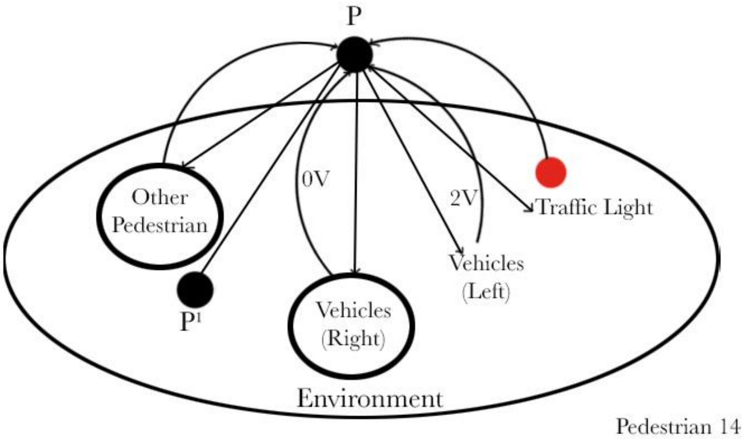


Figure 5.16. Feedback loops for pedestrians who cross on green light.

When pedestrians show non-compliant behaviour by crossing at a red light, they focus on receiving two potential inputs from the other agents in the environment. These inputs are the behaviour of other pedestrians, and the observations relating to vehicles. Figure 5.17 depicts two pedestrians, 14 and 15, who are travelling together. Both pedestrians cross the street when the traffic light is red, and neither of them interacted explicitly to show their intentions. They were little interested in their environment as they searched for vehicles only momentarily while walking towards the pedestrian crossing. That is why in Figure 5.17, we can see one of the primary inputs as vehicles. However, there is also the other pedestrian circled as one of the primary inputs. The reason for that is another pedestrian (pedestrian 13 in Figure 5.18) chose to cross the street just before pedestrians 14 and 15 arrived at the pedestrian crossing. In this example, how pedestrians decide to cross is interpreted according to the situated knowledge of the situation. According to the literature, pedestrians who fall behind other pedestrians tend to cross the street based on the information they receive by observing those other pedestrians (Gupta et al., 2019; Rastogi et al., 2011). Since no explicit interaction or interest in the environment was observed, the cues from pedestrians' behaviours and actions can be interpreted as their crossing decision was influenced by Pedestrian 13. During the decision's implementation, pedestrians 14 and 15 had a brief moment of interest in the vehicles around them, but they were not concerned about any potential conflict. As a result, both their perception level and the pedestrian ahead of them informed them that it was safe to cross.



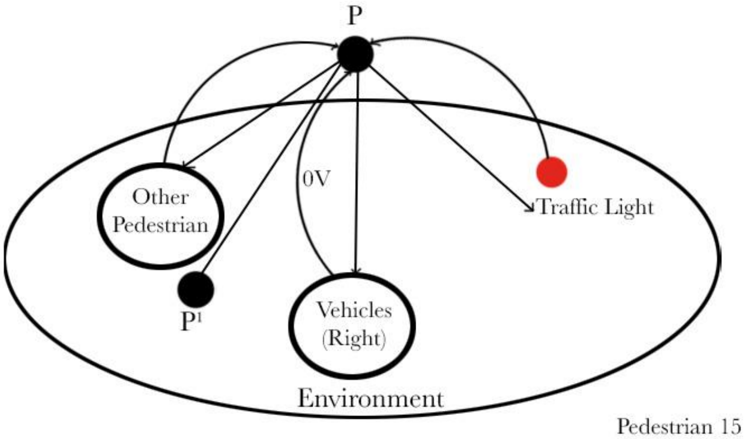


Figure 5.17. Feedback loops for each pedestrian who crosses the street at a red light.

Figure 5.18 shows the feedback loops of pedestrians who evaluate the information they perceive from vehicles. Oncoming vehicles convey information to pedestrians, such as speed and location. This information – the number of vehicles, vehicles' direction, speed, and distance – helps pedestrians determine the level of risk associated with the crossing decision. This risk level is the individual's perception rather than a general indicator (Gupta et al., 2019). Based on their perception, pedestrians decide in which situation they prefer to cross the street. That is why there will be a few types of pedestrians.

Based on the feedback loops, we can see that pedestrian 23 made an explicit interaction by pressing the pedestrian button; however, he then decided to take an opportunity and cross based on the information he received from the vehicles. I classify this type of pedestrian as having *opportunistic pedestrian* behaviour.

Another pedestrian from Figure 5.18 is pedestrian 22, who was not interested much in the environment. Hence, his attention level was low, and he made his decision momentarily with a brief look towards the oncoming vehicles. This type of pedestrian will be referred to as *eager pedestrians*. On the other hand, pedestrians 13 and 26 made informed decisions by observing the environment for a while and acting based on their observations. This type of pedestrian will be referred to as *cautious pedestrians*.

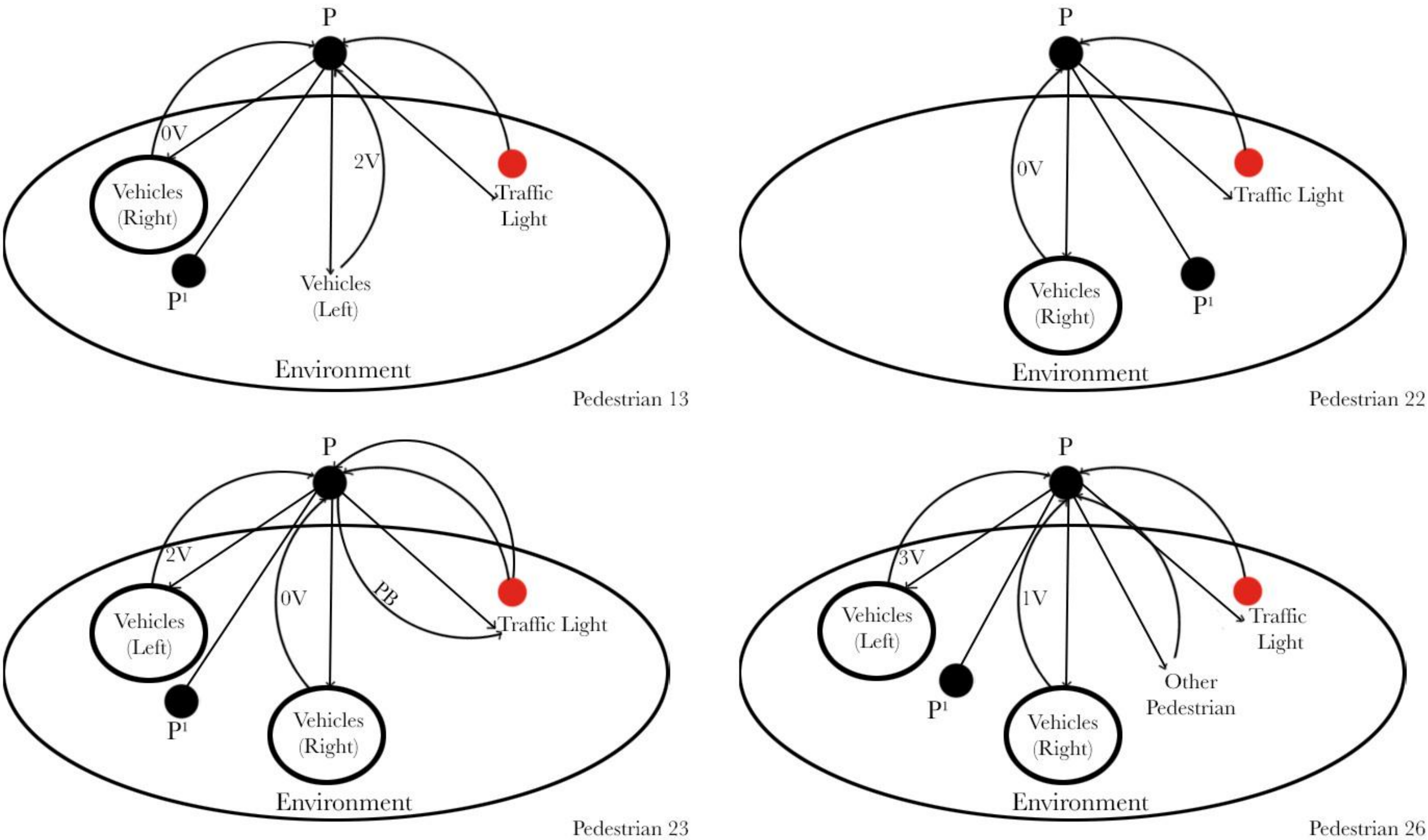


Figure 5.18. Feedback loops for each pedestrian.

Based on their reaction to three types of input (information from (1) traffic lights, (2) other pedestrians and (3) vehicles) coming from the environment, pedestrians are therefore classified into six types; (1) pedestrians who interact explicitly and make their crossing decision based on the regulated infrastructure, (2) pedestrians who do not make explicit interactions and make their decisions based on the regulations in the environment, (3) pedestrians who follow other pedestrians, (4) opportunistic pedestrians, (5) eager pedestrians and (6) cautious pedestrians. In the next section, these groups will be discussed by looking at their behavioural sequence visuals. Following that, a behavioural modules will be provided based on the similarities and differences.

Evaluating Behavioural Sequences for Each Typology

Behavioural frameworks for each typology are constructed by comparing pedestrians' behavioural sequences to one another—comparisons made within the groups described in the previous section. During this process, the aim was to build a skeleton framework based on each pedestrian typology and achieve variations within the typologies through the variables provided by the framework—the variations discovered by comparing pedestrian behaviours. Comparison helped me in identifying similar and dissimilar patterns based on the characteristics found in behavioural sequences. This part of the study will attempt to identify patterns in the sequences, which may differ in terms of their internal processes, situational events, or ethnographic aspects of the environment.

To understand the interactions of a large number of agents, we must first be able to describe the capabilities of individual agents (Holland, 1995, p.7). Holland (1995) explains that it is useful to think of an agent's behaviour as determined by a collection of rules. I focused throughout the feedback loops section on the stimulus-response rules of pedestrians before crossing the street. In this section, I am going to more thoroughly define the agent's behaviours through understanding the set of stimulus and response rules possible for each agent type. These rules are intended to describe the agent's strategies. Here, through comparisons, I select the stimuli and responses which will be represented in the modelling stage. In this study, stimuli are the events and situations observed in the environment, while the responses are the decisions represented by the agents through their behaviours. Identifying possible stimuli and the set of responses given by an agent helps to determine the kinds of rules that each agent type will have. The rules acting in sequence will define the behaviours open to that agent type.

In the next sections, I will be identifying the behavioural sequences of the six (6) groups that were identified in the previous chapter. These groups are:

1. pedestrians who interact explicitly with traffic lights and follow the rules
2. pedestrians who do not make explicit interactions with traffic lights and follow the lights
3. pedestrians who follow other pedestrians,
4. opportunistic pedestrians
5. eager pedestrians
6. cautious pedestrians

Following these sections, I will be discussing the similarities and differences between the behavioural framework of the pedestrian groups in order to refine the groups of behavioural frameworks. In this section, for clarification and representation purposes I have changed the visualisation style and removed the information related to the vehicles passing by the junction. The visualisation style changed from Figure 5.19 to 5.20. I have included only the vehicles which passed by the road that pedestrians were about to cross. This is done in order to increase the readability of the visualisations and make them easier to understand and follow. The outline of the visualisation changed from horizontal to vertical in order to fit the page, so that the words are more readable. In the updated version, the time, traffic light and pedestrian behaviours were represented vertically. Vehicles were represented as grey boxes in various lengths. These lengths aimed to represent their temporal presence in the street.

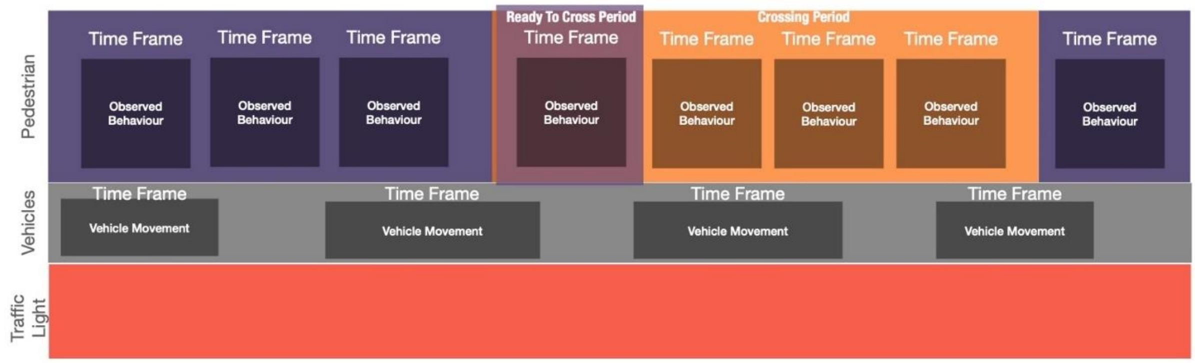


Figure 5.19. Original behavioural sequence visualisation.

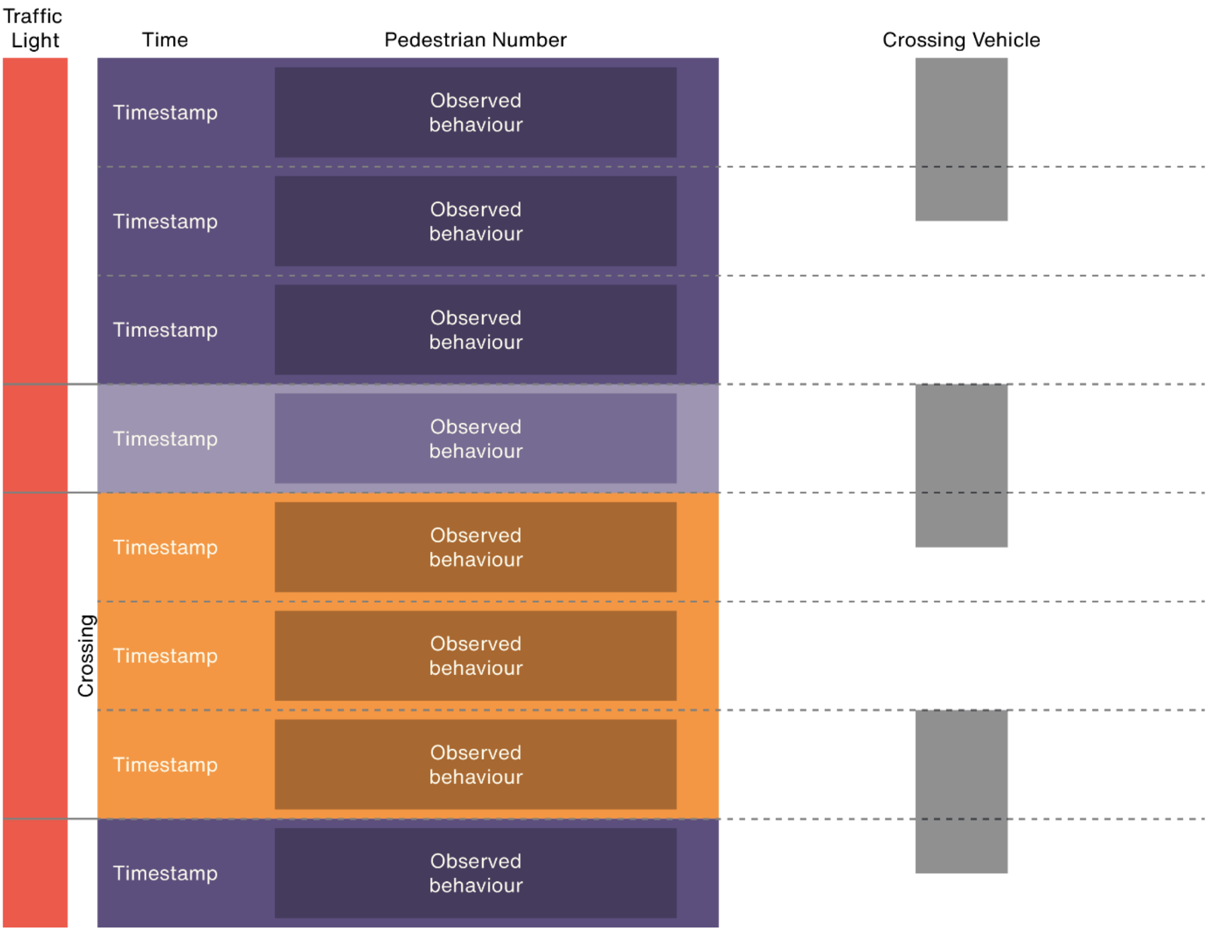


Figure 5.20. Reorganised behavioural sequence visualisation to improve graphical clarity.

Pedestrians who interact explicitly with traffic lights

In the video recordings sample, some pedestrians relied on triggering the traffic signals through push buttons to show their intention to cross and they crossed when the light for pedestrians turned green. The distinguishing factor for these pedestrians from the second group is their explicit interaction with the infrastructure.

In terms of behavioural process, the pedestrians who interacted with the traffic lights all followed similar behavioural sequences. They all pressed the push button, waited until the light was green and crossed. However, there were subtle behavioural differences when they were complying with the rules. Here, I give as examples two behaviour sequence maps that have certain differences. One obvious difference that can be immediately identified is the temporal difference between them. Whilst one pedestrian waited a very long time for the pedestrian light to turn to green, the other waited ⅓ of it. This difference was observable through their behaviours. For example, when we look into both visualisations, it can be seen that Pedestrian 24 (Figure 5.21) was significantly less interested in the environment than Pedestrian 40 (Figure 5.22). Most of the waiting period, Pedestrian 40 was trying to understand the environment, looking in different directions to observe the oncoming vehicles. When I was observing the video, I expected him to cross as his behaviour resembled more cautious pedestrians than pedestrians who interact explicitly and follow the rules. However, he waited until the light was green even though (as can be seen in the note and the image) his gestures looked like he was uncomfortable.

On both occasions the vehicle volume was high in the environment. However, when Pedestrian 24 was waiting, there were other pedestrians around him who started to cross. In addition, one vehicle in the closest lane to him was already stopped and waiting for pedestrians to cross. Pedestrian 24 did not take these into consideration as he only started to cross when the pedestrian light was green.

Another difference between them was that when they were crossing, Pedestrian 40 was still observing the routes that he was entering, even though the pedestrian light was green. In contrast, Pedestrian 24 is assumed to be not interested in the environment as he was looking towards the ground and not around him.

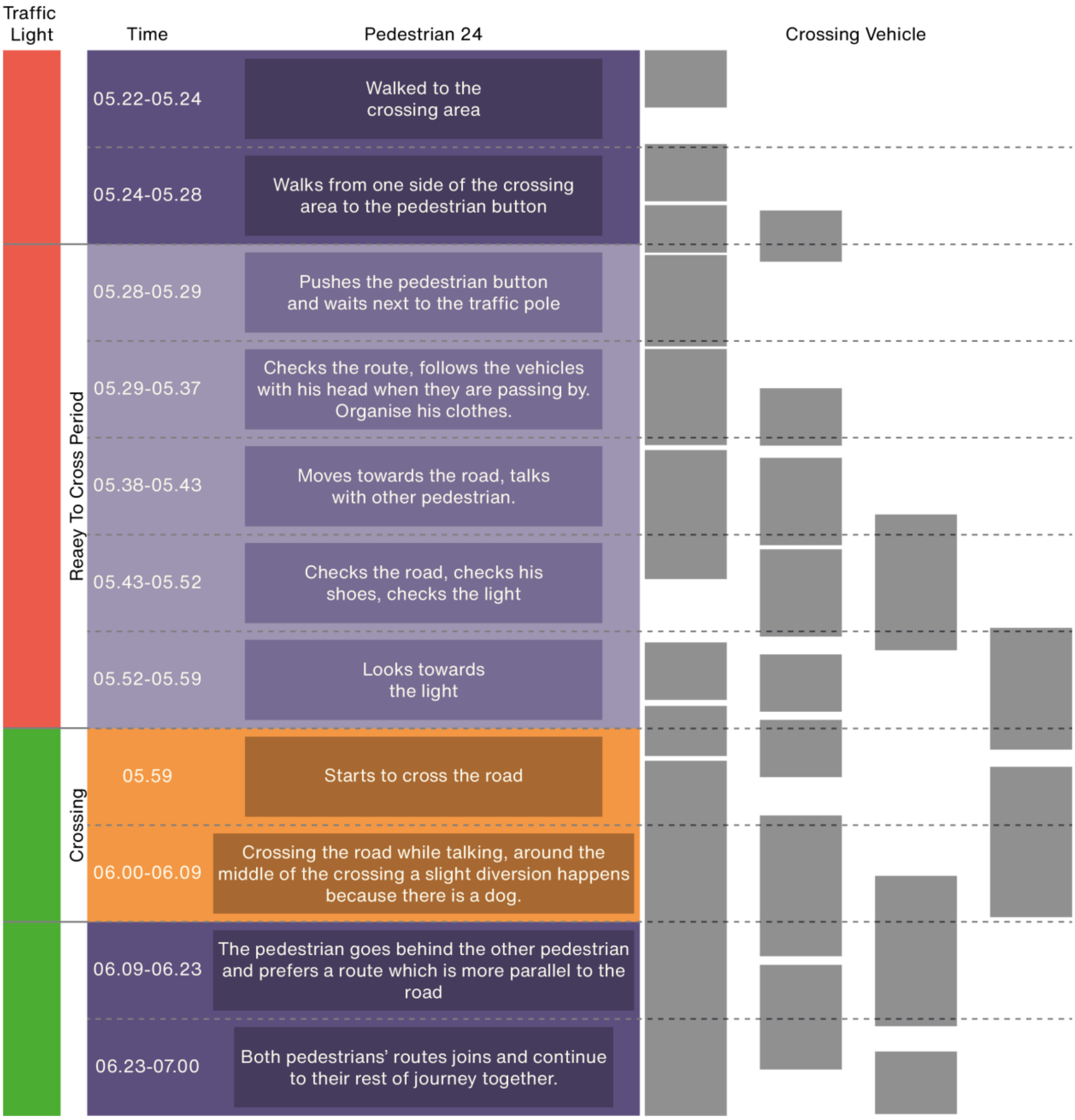


Figure 5.21. Behavioural Sequence of Pedestrian 24 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

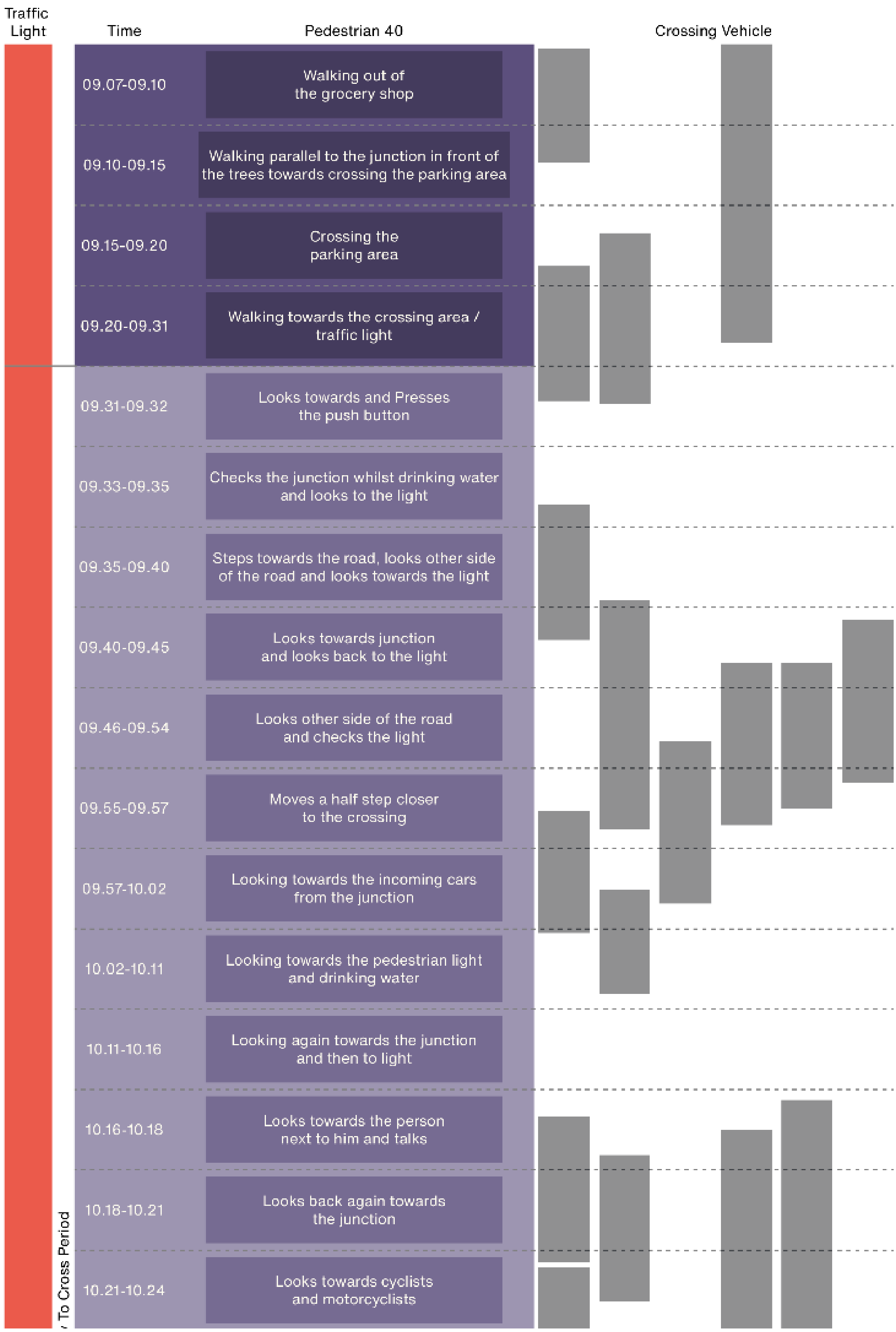


Figure 5.22. Behavioural Sequence of Pedestrian 40 (continues next page), showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

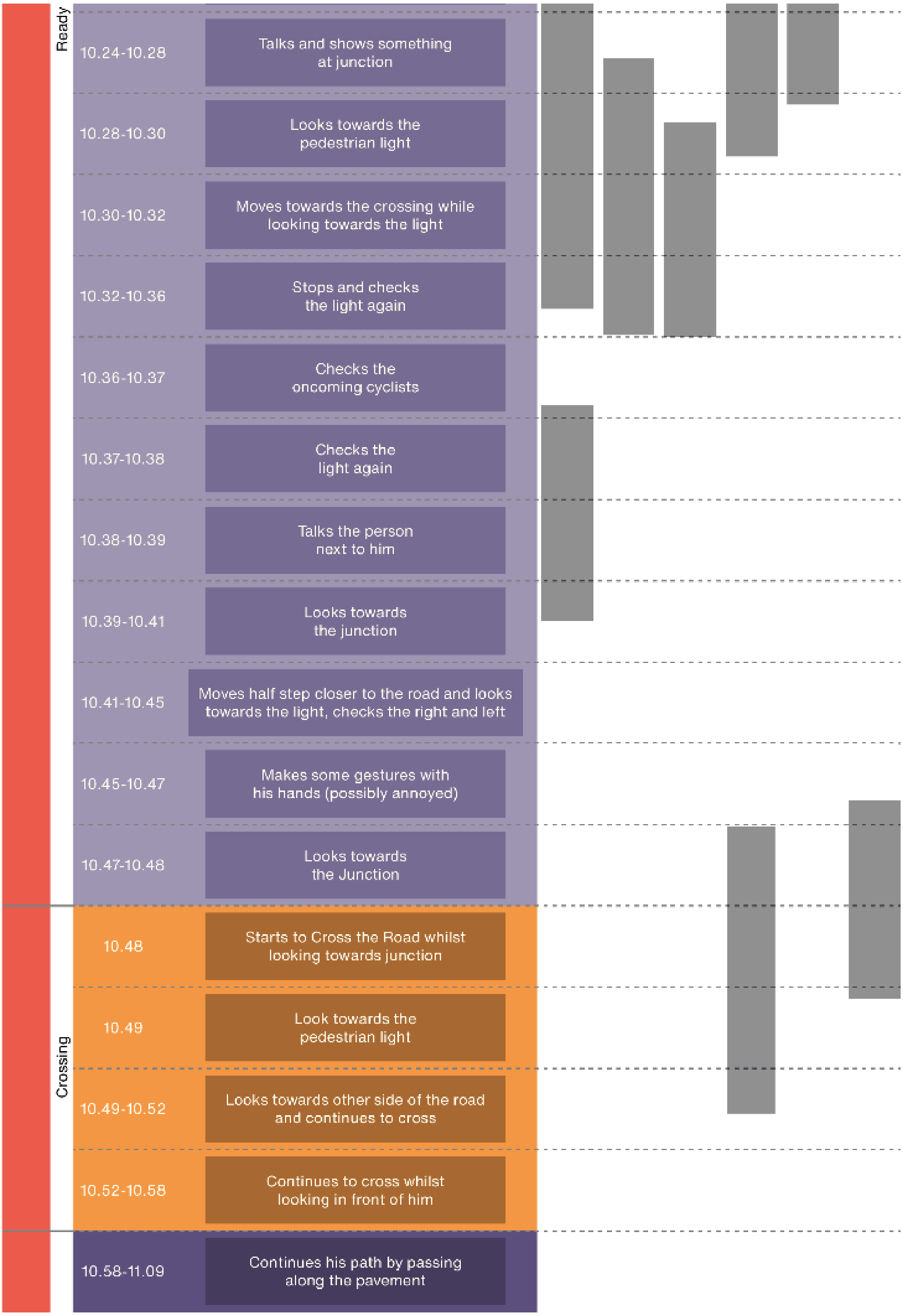


Figure 5.22. Behavioural Sequence of Pedestrian 40 (continued), showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

Pedestrians who do not make explicit interactions with traffic lights

In this second pedestrian group, the focus behaviour was crossing the street when the pedestrian light is green but not using the push button. This behaviour occurred slightly more often than the pedestrians who used the push button. Here, I have given as examples the behavioural sequences of Pedestrian 27 and Pedestrian 28 through the Figure 5.23 and 5.24. respectively.

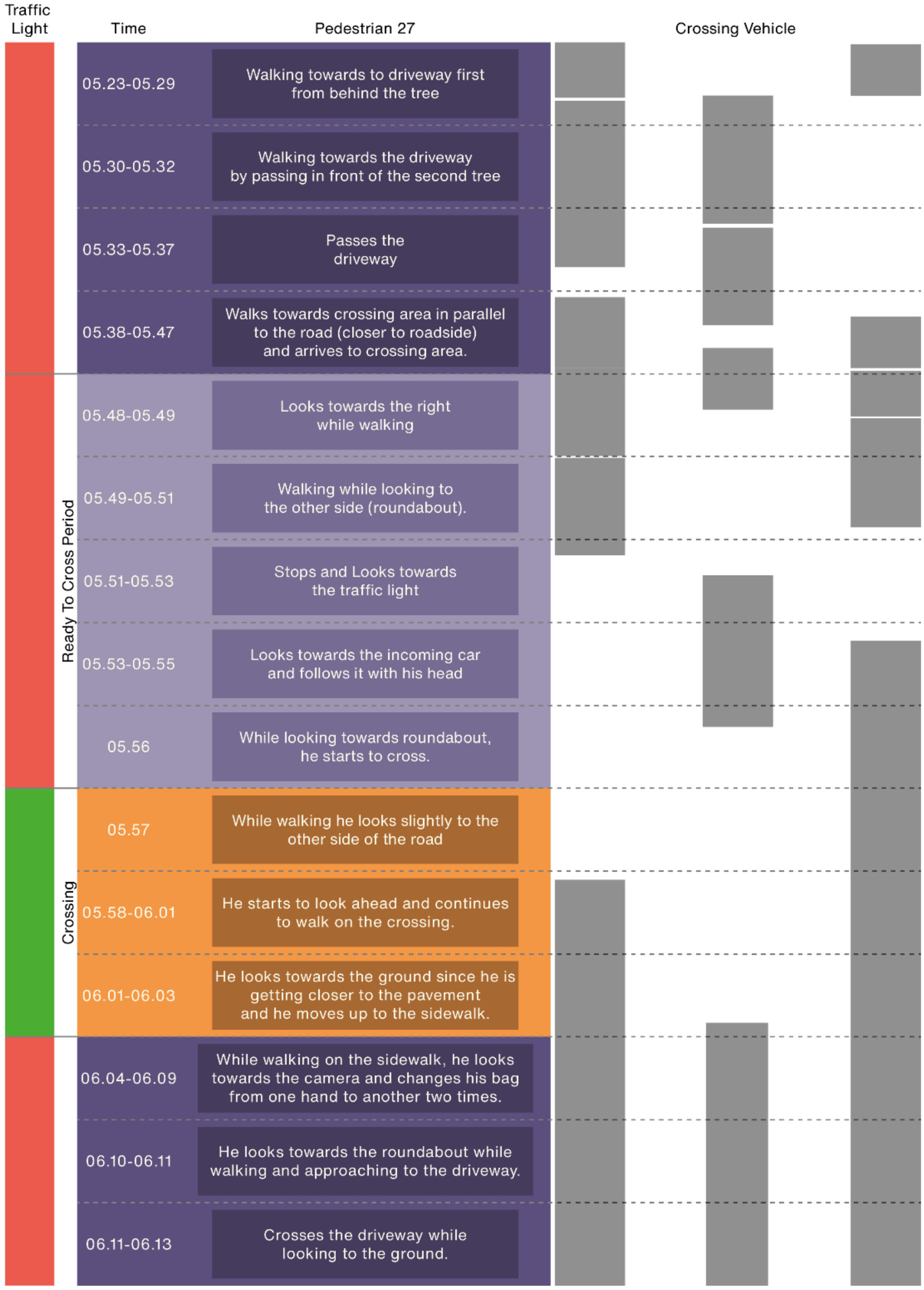


Figure 5.23. Behavioural Sequence of Pedestrian 27 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

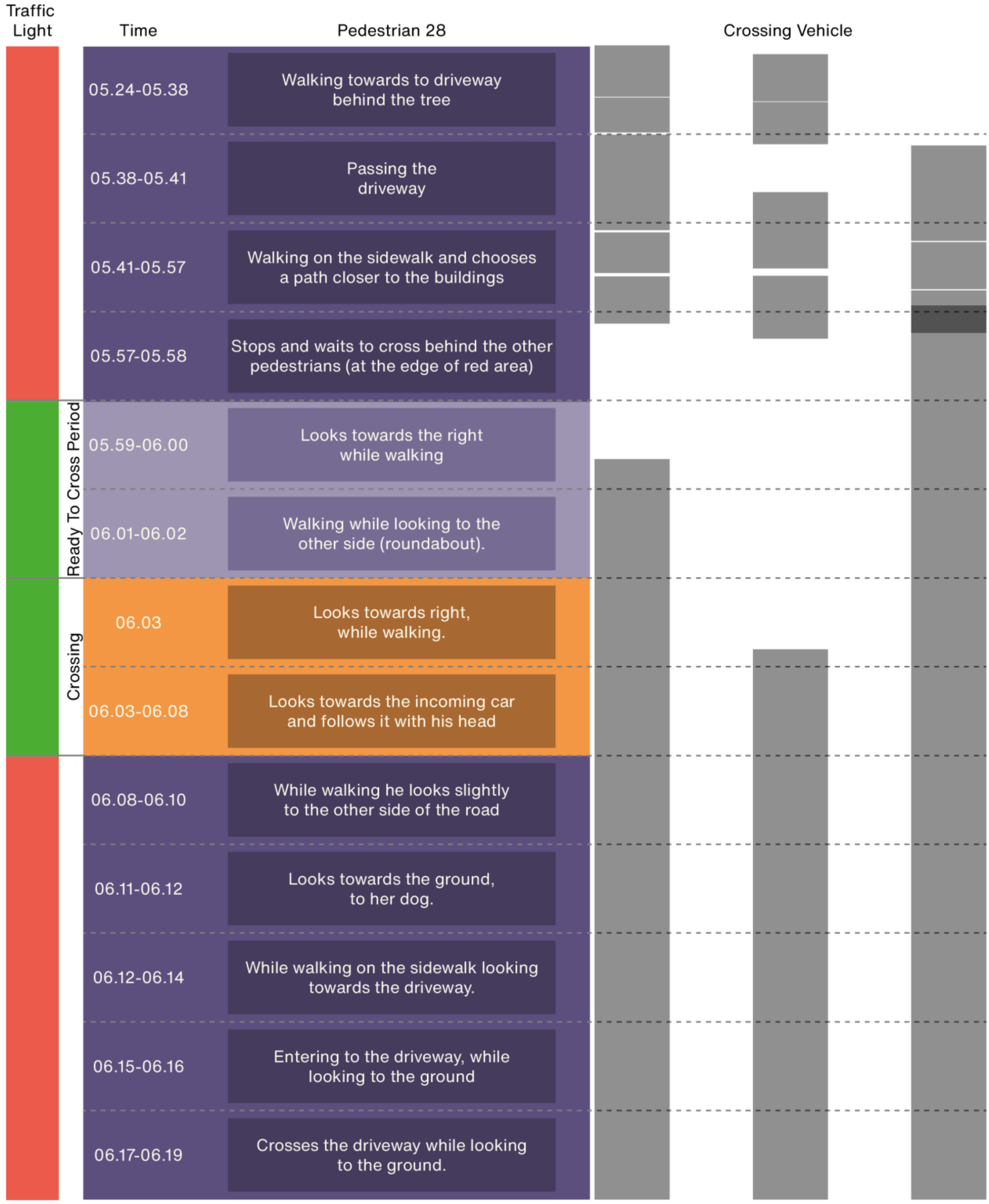


Figure 5.24. Behavioural Sequence of Pedestrian 28 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

The overall pattern of pedestrians showed similarities on the main aspects of the behavioural sequence, which can be outlined as reaching to the crossing area, waiting for the pedestrian light to turn green and crossing. In this group, one of the patterns was that when pedestrians arrived at the crossing area, there were already other pedestrians waiting at the traffic light. Therefore, it might be possible that some of the pedestrians in this group were not interacting with the push button because there were already other pedestrians waiting.

One difference between the Pedestrian 27 and Pedestrian 28, as it can be seen from the behavioural sequence visualisation, is that Pedestrian 27 were more interested in the environment than the Pedestrian 28. By more interested, I mean that Pedestrian 27 was looking and tracking passing vehicles with his head movements whilst Pedestrian 28 was looking towards the traffic light and not at passing vehicles.

Pedestrians who follow other pedestrians

Pedestrians who follow other pedestrians represent the group of pedestrians who make their crossing decisions based on their observation of other pedestrians. Only pedestrians who seemed to be influenced by other pedestrians when deciding to cross the road were included in this group. Pedestrians who waited because other pedestrians were waiting, on the other hand, were not included because the observation data for this kind of grouping was not adequate. This inadequacy of observation was most apparent in this group as when looking at these pedestrians the perceptual information was not only related to vehicles and infrastructure conditions but also to other pedestrians. This meant adding another variable to the consideration when deciding what information made them act or not act.

The reason for this complication is primarily because when other pedestrians were crossing the road, there were indications that they were assessing the situation such as their head movements. However, in this group, the pedestrians assessed the infrastructure and vehicles very briefly and most of them crossed even without stopping. This suggests they could also be in the group of eager pedestrians. However, their difference from the eager pedestrians was that there was another pedestrian in front of them who was crossing the road already. This meant that they could have briefly assessed, and also been influenced by, the crossing pedestrian or they have only briefly assessed the environment. Due to a lack of indication through their actions about the basis of their crossing decision, this pedestrian group was one of the most challenging to identify and assess. Therefore, in addition to video observation, other sources of data should be employed to track these kinds of behaviours.

To give examples through the Figures 5.25, pedestrians 14 and 15 were travelling together and they were briefly interested in traffic and traffic lights. Just before they started to cross, there was already another pedestrian crossing the road and they followed after her without stopping. During their crossing period, only one of them, Pedestrian 15, checked the road for a moment whilst entering the crossing area.

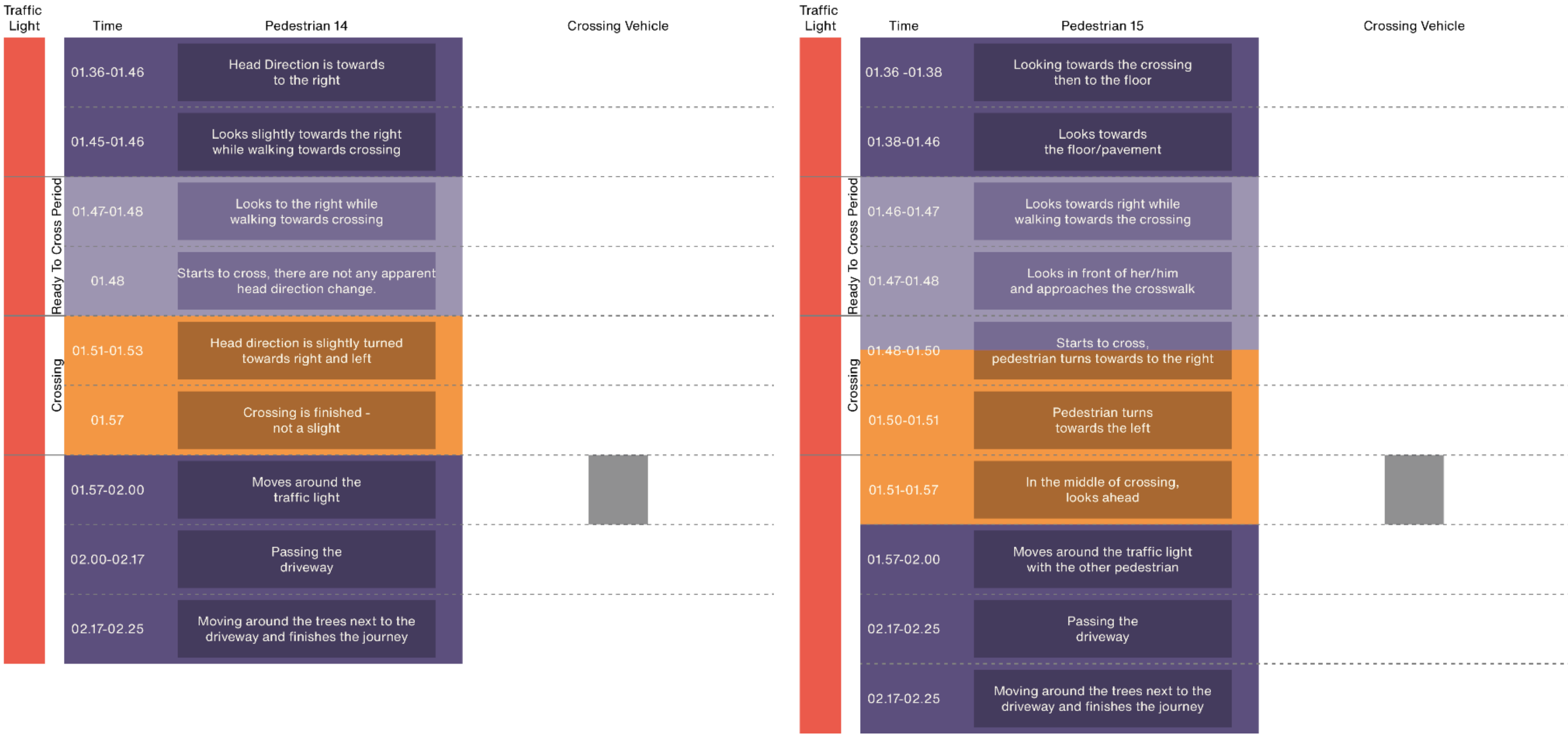


Figure 5.25. Behavioural Sequences of Pedestrians 14 and 15 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

Pedestrian 34, on the other hand, followed a different behavioural pattern in Figure 5.26. He interacted with traffic infrastructure by pressing the push button, although he was usually distracted and, on his phone, with his back towards the crossing. When he was waiting, he was in front of other pedestrians. When he noticed several pedestrians were moving, he turned around and began crossing.

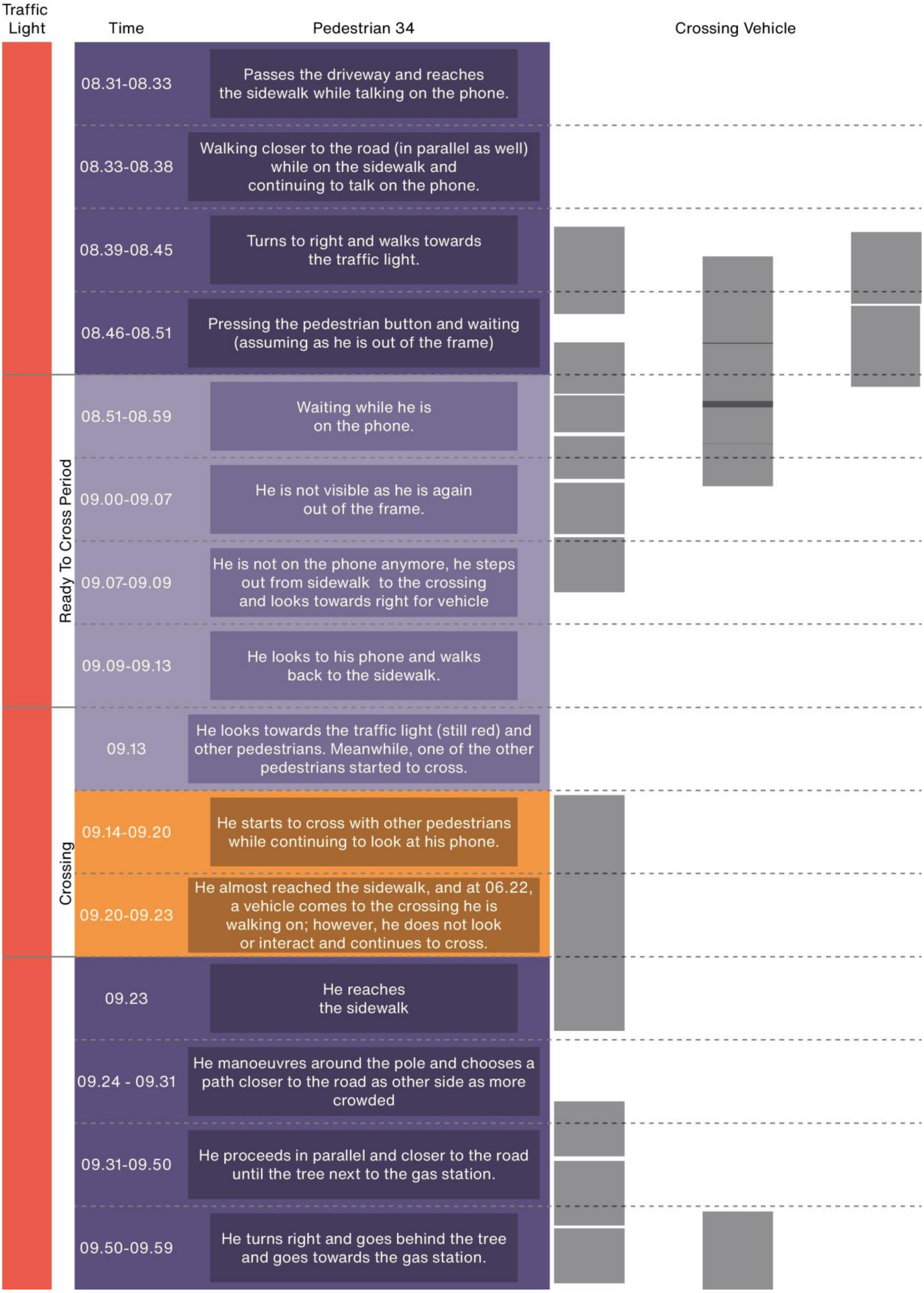


Figure 5.26. Behavioural Sequence of Pedestrian 34 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

This group of pedestrians had two things in common: (1) they were frequently distracted or did not spend significant time checking the traffic conditions and (2) throughout their crossing period, the pedestrian light's condition did not change, always showing red. The distinction between them was their waiting behaviour. However, this waiting and not waiting can be dependent on the timing of other pedestrians' actions, or the density of the traffic.

Opportunistic pedestrians

The opportunistic pedestrians represent pedestrians who have an explicit contact with the infrastructure via pressing the push button; yet, if there is an availability in the road, they take the opportunity to cross. They are, in terms of risk-taking behaviour, in between the eager and cautious pedestrians. Therefore, they are more attentive and observant than eager pedestrians whilst less hesitant than cautious pedestrians. These assumptions of attentive, observant and less hesitant are based on their waiting time, head movements and actions.

All the opportunistic pedestrians in the recordings observed their environment before crossing. They all pressed the push button but did not wait for the pedestrian lights to turn green. Most of them took risks when they were crossing the street. For example, in both examples Figure 5.27 and Figure 5.28, they increased their speed whilst crossing the street and aimed to complete their crossing when they saw vehicles approaching.

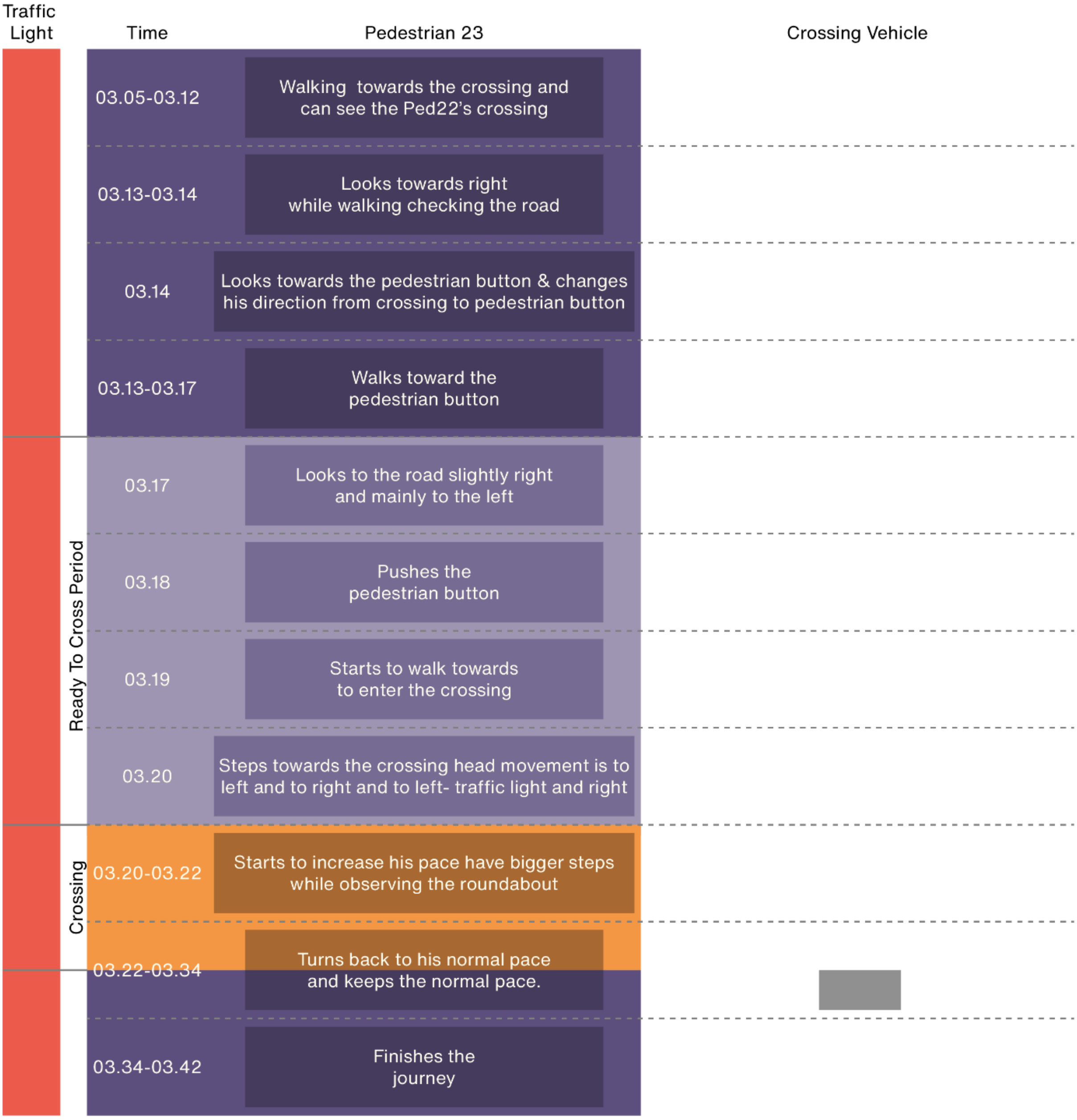


Figure 5.27. Behavioural Sequence of Pedestrian 23 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

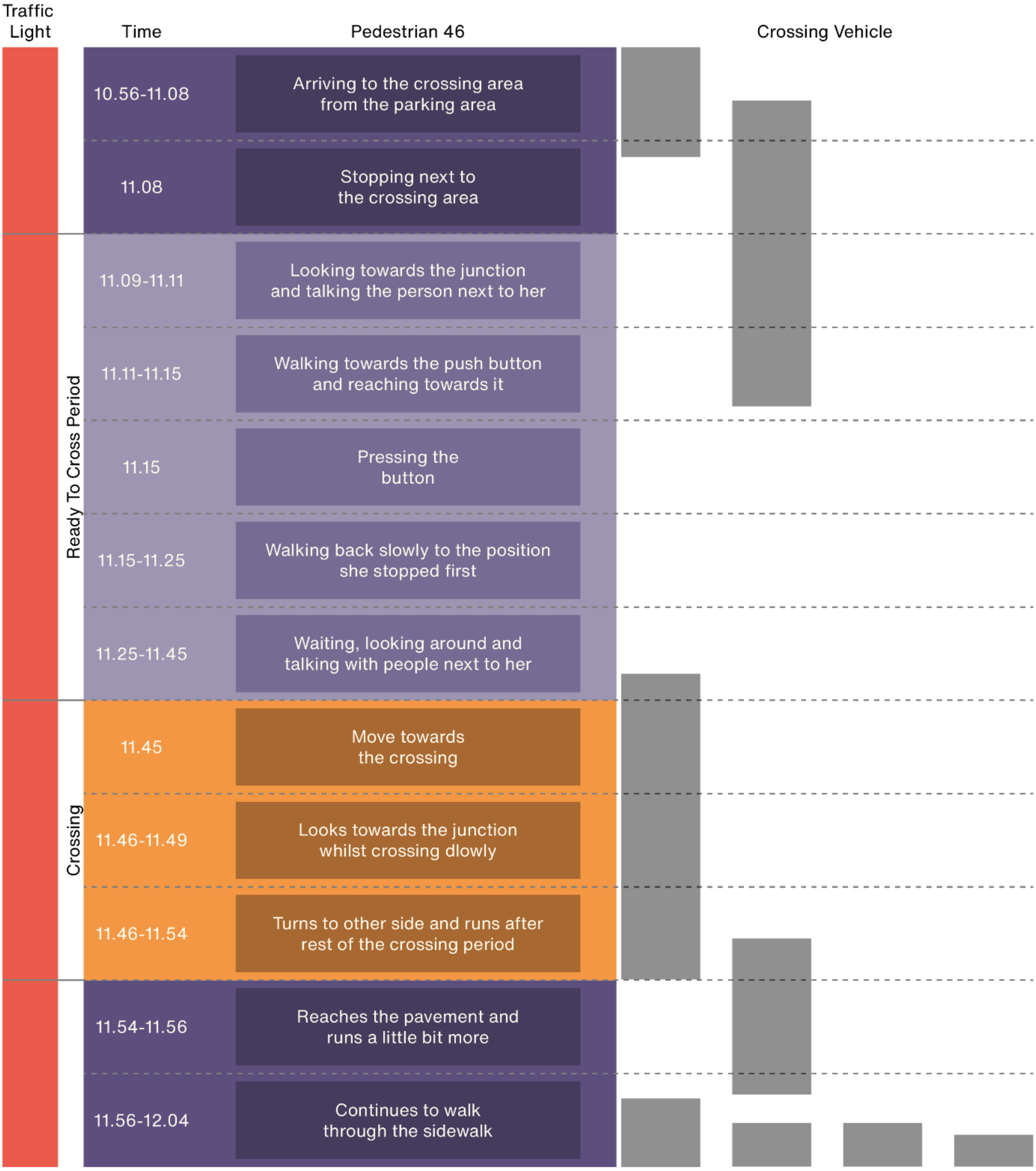


Figure 5.28. Behavioural Sequence of Pedestrian 46 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

The differences between Pedestrian 23 (Figure 5.27) and Pedestrian 46 (Figure 5.28) were their waiting time and the situations they were in. Pedestrian 23 crossed the street just after he pressed the push button as there was no oncoming traffic and he sped up towards the middle of the road whilst looking towards the junction.

Pedestrian 46 on the other hand, did not take immediate actions. She arrived at the crossing area, went towards the push button and then turned back to the position she arrived at. She waited there for a while and when she realised there was no traffic on the road, she decided to cross. She looked like she was less observant than the Pedestrian 23 before she started to cross. When she stepped towards the crossing, she looked towards the junction and saw the oncoming traffic. At that point, instead of stepping back to the pavement, she decided to move forward and increase her speed until she crossed.

As a result, Pedestrian 46 performed a riskier behaviour than Pedestrian 23 as she was less attentive before starting to cross. This can show that even the pedestrians who are in the same group can show differentiations in terms of risk-taking levels.

Eager pedestrians

The eager pedestrians were identified as those who examine the road momentarily before moving to the crossing when the pedestrian light is red. Figures 5.29 and 5.30 show two separate pedestrian behavioural sequence visualisations discussed in this section. When crossing the road, the majority of the pedestrians in this group monitored only one side. Both Pedestrians 22 and 39 can be seen turning their heads before crossing solely towards oncoming vehicles from the closest lane. Since they spend minimal time interacting with and observing their surroundings, they spend the least time in the observed street area. When people crossed the street, their speeds varied. While Pedestrian 22 upped his speed and ran till he crossed the road, Pedestrian 39 maintained the same pace throughout his journey.

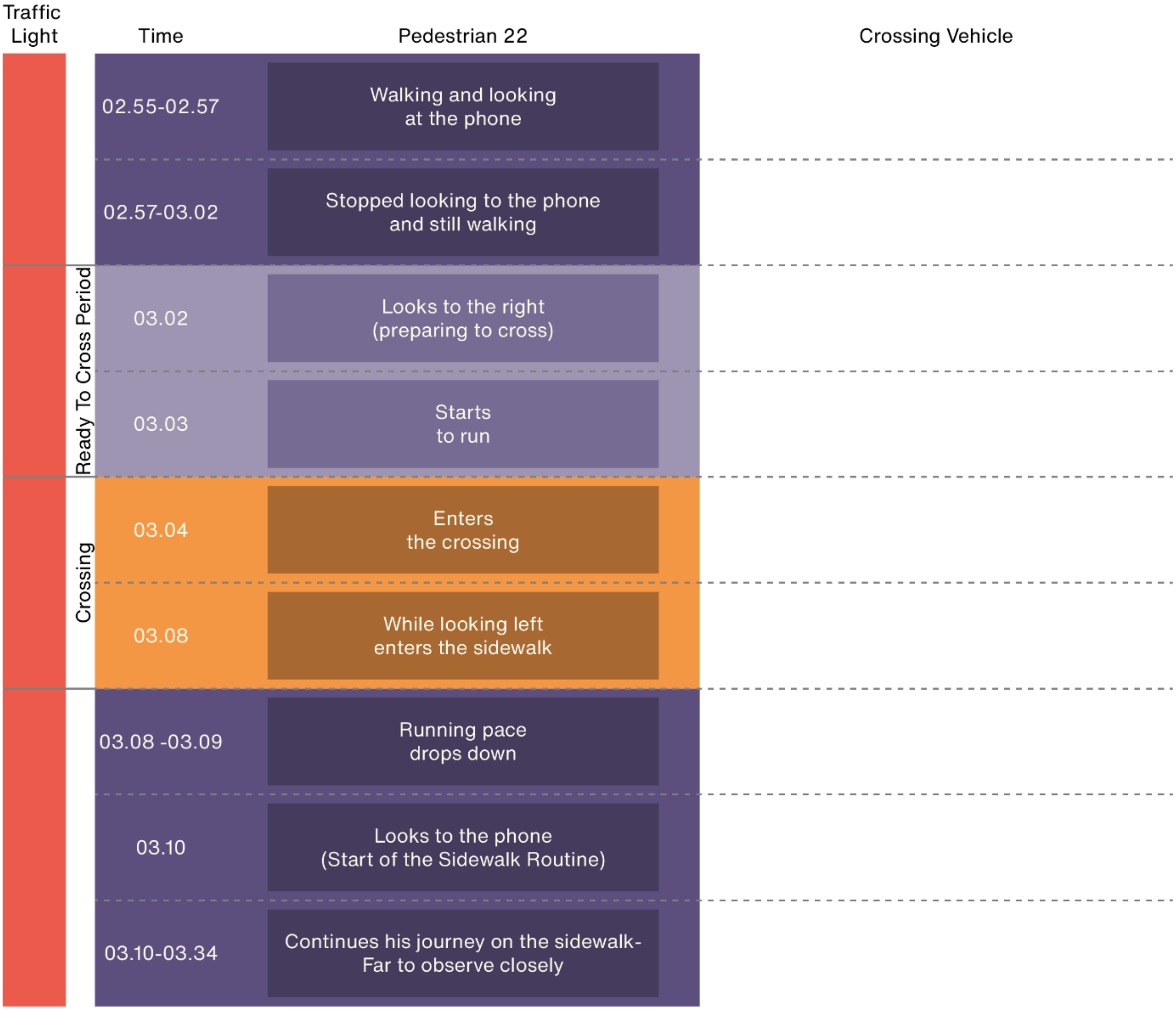


Figure 5.29. Behavioural Sequence of Pedestrian 22 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

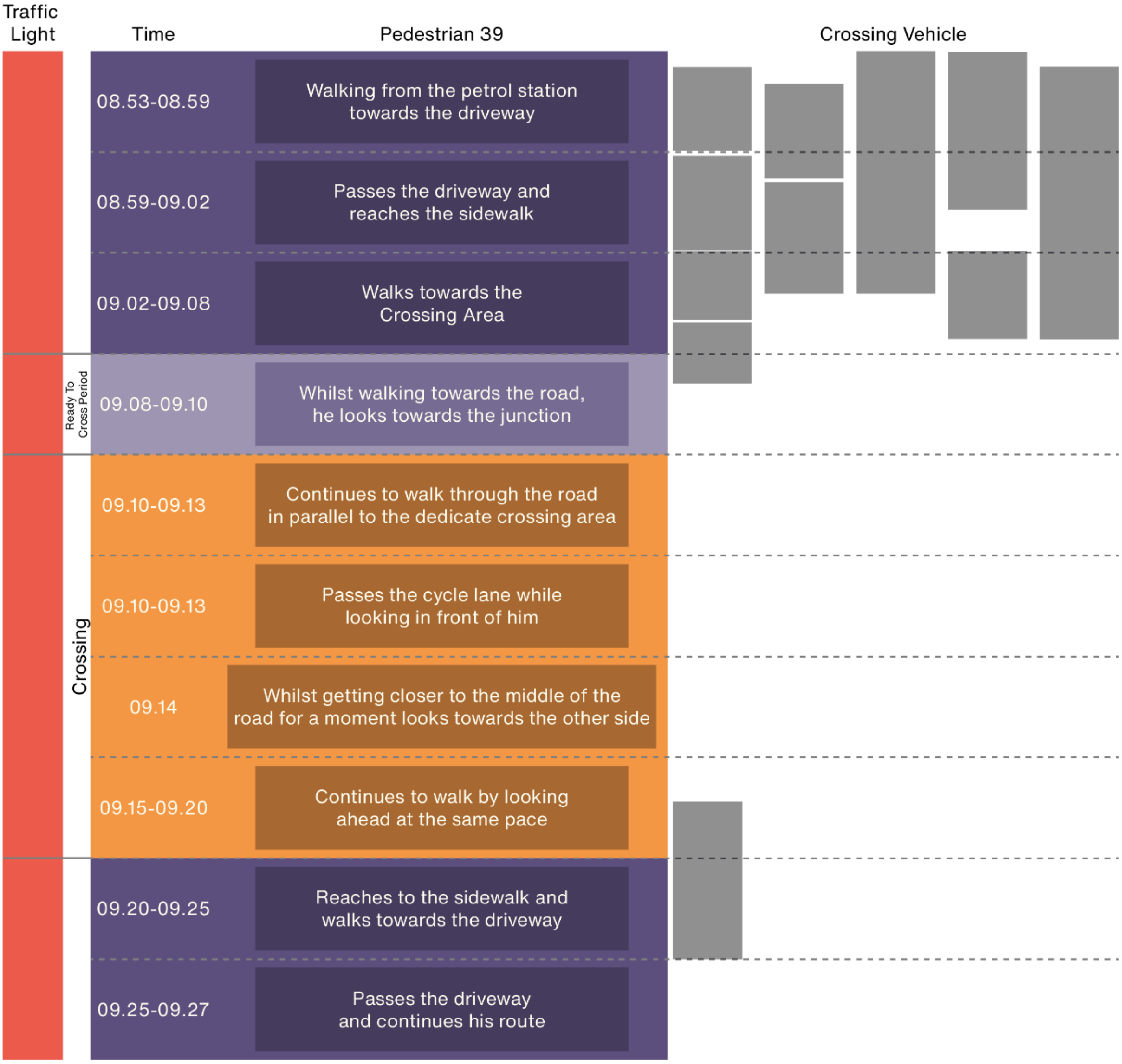


Figure 5.30. Behavioural Sequence of Pedestrian 39 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

Cautious pedestrians

Cautious pedestrians describe pedestrians who examine the street conditions in order to obtain reassurance based on the vehicle's speed and distance. They assess the distance and speed of vehicles in order to identify a safe gap to cross. They have a higher safety margin than other pedestrians. They choose to cross the street when there are no or few vehicles on the road. When there are vehicles surrounding them, their decision-making about crossing the road takes longer than it does for eager and opportunistic pedestrians.

In Figure 5.31, Pedestrian 13 approaches the crossing and stops in order to observe the nearby vehicles at the junction. Once the vehicles on the junction turn towards another way and are no longer in conflict, she decides to cross the road. When she is crossing, the pedestrian light is red and there are no vehicles or pedestrians around. During her journey, she does not change her speed.

Figure 5.31. Behavioural Sequence of Pedestrian 13 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

When Pedestrian 26 arrives at the crossing area in Figure 5.32, he is more active than Pedestrian 13 and moves around, checking vehicles at junctions and in other directions. He double-checks the junction just before crossing to make sure there are no vehicles in conflict. Then he looks in the opposite direction and notices that the closest vehicle is stopped, so he enters the crossing.

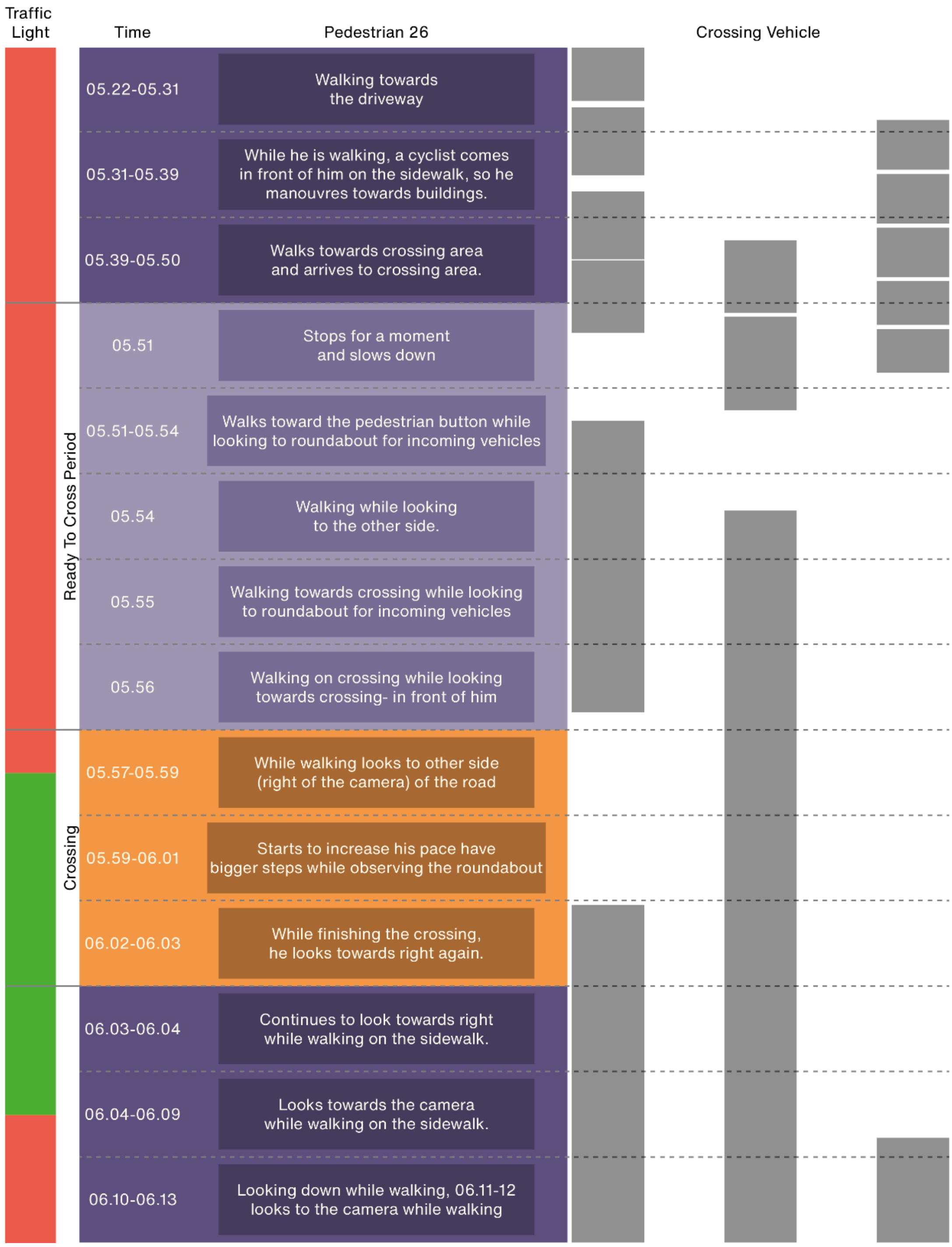


Figure 5.32. Behavioural Sequence of Pedestrian 26 showing, from left to right, traffic light conditions, higher-level actions (ready to cross, crossing, etc.), temporal data, lower-level actions and vehicle presence.

Overall, both examples show that pedestrians under this group spend a certain amount of time before crossing in order to avoid any approaching vehicle or dangerous situation. Whilst some of them, like Pedestrian 26, show more hesitant and active behaviours (such as moving around and assessing the situation carefully), others, like Pedestrian 13, were more passive and waiting until there is a safe environment available to them.

Identifying the Behavioural Modules Necessary for the Simulation

I identified a number of modules based on the observed pedestrian groups in order to develop a framework for a pedestrian agent-based model. In this section, I will be explaining these modules briefly and use them in the following chapter. These modules include (1) traffic light compliance behaviour, (2) explicit interaction with traffic light (3) long distance perception of traffic before crossing behaviour performed, (4) perceiving the potential dangers (5) acting according to the perceived dangers (6) crossing outside of the dedicated crossing area, (7) increasing the speed whilst crossing the road.

Traffic light compliance behaviour is based on the first two categories where pedestrians followed the pedestrian light when they decided to cross. The *explicit interaction with traffic light* refers to pedestrians approaching the traffic pole in order to press the button. *Long distance perception of traffic before crossing is performed* refers to the pedestrian's comprehension of the road situation before they act to cross the road. This module is based on the opportunistic pedestrians, eager pedestrians and cautious pedestrians. *Perceiving potential dangers* was based on the same modules and aimed to identify the potential dangers by evaluating their comprehension of the situation in order to make a decision to cross or wait. *Acting according to the perceived danger* or traffic lights refers to the crossing or waiting actions that need to be taken based on the pedestrian's perception and evaluation. *Crossing outside of the dedicated area* was observed in numerous pedestrians such as Pedestrian 27 (in the pedestrians who do not make explicit interactions with traffic lights group). This aims to give a level of freedom when pedestrian agents are moving in the simulation. *Increasing the speed whilst crossing the road* is another behaviour that occasionally occurred during the observations (e.g. Pedestrian 46 in opportunistic pedestrian group). I found this aspect useful to model as it shows the different rhythm of pedestrians.

Even though I have discussed various behavioural aspects of pedestrians, as a starting structure my aim was to demonstrate different risk-taking behaviours and formulate them in order to translate them to the simulation. This structuring of the behavioural analysis aimed to provide a modular framework for the agent-based simulation.

One aspect of the previously defined group is not included here, which is the behaviour of following other pedestrians during the crossing period. Even though defined under this name, this group's behavioural analysis was slightly more complicated than others. The following behaviours are observed to be supplementary to pedestrian's perception as they were often looking towards the traffic and vehicles as well as other pedestrians. Therefore, in this stage, I have not modelled this module. However, with further research on following behaviour and how much effect it has on decision making during road crossing, this behavioural module can be implemented into the simulation as well.

Once this modular structure is achieved, additional features can be added based on the discussions and observations reported in here. For example, pedestrian agents can show annoyed or restless behaviours when they wait too long. These kinds of playful additional aspects can perhaps enable richer input when developing and planning interventions.

Chapter 6 Creating the Artificial Pedestrian Society

Building on the video observation chapter, this study introduces the artificial pedestrian society created in this PhD. The term 'artificial pedestrian society' refers to the pedestrian simulation produced using agent-based modelling. An agent-based model (ABM) is a computational model that allows researchers to describe, develop, analyse and experiment with social processes composed of autonomous and heterogeneous agents in a given context (Salgado and Gilbert, 2013). It helps to represent and test social theories which researchers cannot easily describe using mathematical models (Axelrod, 1997). ABM is particularly beneficial to constitute macroscopic phenomena of interest by describing the micro-level mechanisms, behaviours or patterns (Filomena and Verstegen, 2018; Salgado and Gilbert, 2013).

At the end of the theoretical framework, the main research question of '*how to design a pedestrian-centric street system that dynamically manages street mobility*' was divided into *how to design* and *how to experiment.* Whilst the first part looked into defining pedestrian behaviours, interactions, and their context to design a tool, the second part aimed to explore how to iterate, implement, evaluate, and test the interventions. In a sense, agent-based modelling serves as a bridge between these two parts of the research question. By framing pedestrian behaviours and interactions further to describe and visualise the pedestrian crossing dynamics in the street, agent-based modelling addresses the first part. Furthermore, it addresses the second part by providing a platform for experimenting and iterating interventions that can challenge the existing constraints in the street for pedestrians.

Agent-based modelling is found particularly useful in this research for several reasons. One of them is its bottom-up approach to modelling, where the system emerges from the individual behaviours and actions (Crooks et al., 2008). The bottom-up approach supports the human-centred design approach of this PhD by focusing on the different individual behaviours exhibited by pedestrians and representing them in the system. This approach helps enhance the understanding gained through video observations about pedestrian movement and behavioural patterns in the street environment and their relationship with the vehicles and infrastructure. Furthermore, by having the ability to represent different pedestrian behaviours, it creates a platform for experimentation.

One of the fascinating properties of agent-based modelling is that even though agents are dependent on a set of rules, they can show complex behavioural patterns. This feature grounds agent-based modelling in complexity thinking and allows studying emergent processes (Schulze et al., 2017). This dynamically interacting feature of the agent-based model allows us to model a system that has real-world-like complexity (Craenen and Theodoropoulos, 2011). Therefore, another reason to use agent-based modelling in this research is its ability to represent the dynamic and complex relationships in the street environment.

Another important reason to use agent-based modelling is its iterative nature which enables refining, testing, interacting and comparing the same model through different inputs (Schlüter et al., 2019). Its iterative nature gives a level of flexibility about changing or intervening in the model. In this research, this change happens by adding design interventions, which will be explained further in the next chapter.

Through addressing the research question from two aspects, agent-based modelling carries two purposes: (1) expanding the description of pedestrian behavioural processes by framing and visualising them with their context and (2) offering an experimentation space for design interventions that can challenge the constraints in the real street environment. In this chapter, I will first offer a literature review of pedestrian simulation, and then explain the process of translating the video study into the simulation. The following section describes the pedestrian simulation following the ODD (overview, design concepts and details) protocol by Grimm et al. (2006). Then, I will conclude the chapter with analysis and discussion sections.

Literature Review of Pedestrian ABM Simulation for Crossing Behaviour

In various disciplines, there are many studies that have addressed the issue of simulating pedestrian behaviours. A large number of pedestrian simulations focused on crowd simulations (e.g. Qu et al., 2019) and pedestrian simulation of spatial activities such as navigation (e.g. Crooks et al., 2015; Karmakharm et al., 2010; Kerridge et al., 2001). In this research, my main focus was the pedestrians and their relationships with vehicles. Therefore, I have particularly focused on the pedestrian's crossing periods where they need to interact with a number of different variables such as street infrastructure and vehicles. Hence, in this section, I will primarily focus on the studies that simulate pedestrians during their crossing period. In here, rather than saying pedestrian crossings, I specifically say 'crossing period' because pedestrians do not necessarily always cross at official pedestrian crossings.

Pedestrian simulations that are looking for critical factors influencing walking movement and pedestrian decisions during their crossing period incorporate various methods such as cellular automata (e.g. Schadschneider, 2001), statistical models (Saleh et al., 2020; Zhang et al., 2018), social force (e.g. Liu et al., 2017; Zeng et al., 2014; Zhou et al., 2019) and agent-based modelling (Shaaban and Abdelwarith, 2020; Zhu et al., 2021). For example, the cellular automata approach treats pedestrians as occupied states of cells and their interactions occur through the cells (Schadschneider, 2001). Statistical models represent the probabilities and aim to produce quantitative data for developing strategies (Zhang et al., 2018) or evaluation purposes (Saleh et al., 2020). Social force models represent pedestrians as particles that are subjected to forces such as desired velocity, attraction and repulsion in an analogy from fluid dynamics (Zhou et al., 2019). These fluid models are found appropriate to more extreme events such as evacuation scenarios where densely packed crowds present (Helbing et al., 2005). Torrens (2011) mentions that this approach is not suitable for realistic representation of individual movement. On the other hand, agent-based modelling represents pedestrians as heterogeneous, autonomous and situated entities moving according to behavioural rules and specifications. Therefore, I have chosen agent-based modelling to create a pedestrian simulation that provides an exploratory space with a wide range of pedestrian behaviours. In ABM, each pedestrian is studied as an agent and assigned specific attributes in order to respond to complex settings in the environment. The agents behave independently which makes ABM a suitable technique for modelling pedestrian movements (Kerridge et al., 2001; Turner and Penn, 2002). These types of models offer a detailed representation of behaviours therefore can overcome some of the limitations of the other methods.

The use of agent-based modelling of pedestrians in the context of street crossing and negotiating with vehicles is considered in a number of ways throughout the literature. One of them is modelling pedestrian and vehicle interactions in unsignalised marked-crossings (Godara et al., 2007; Shaaban and Abdelwarith, 2020; Shaaban and Abdel-Warith, 2017; Zhu et al., 2021). In these examples, one of the most common aspects to look at is the gap between the pedestrian and vehicle before crossing. For example, Shaaban and Abdelwarith (2020) looks specifically for perpendicular crossing paths where pedestrians evaluate the gap between themselves and the vehicle closest to them. Another example by Zhu et al. (2021) analyses unsignalised mid-block pedestrian crossings with refuge islands. One of the common points among these examples is that there is only one dedicated space for pedestrians on the road and there is no freedom of movement during their crossing period. For example, they cannot cross at any place except the dedicated area that is an officially sanctioned crossing. In addition, the pedestrian's speed does not change and the modelling does not address what happens during conflicts. This limits the potential experimentations in the simulation space, such as removing or altering the dedicated crossing, or changing the spatial layout. Therefore, these simulations are most often used as risk assessment (Shaaban and Abdelwarith, 2020; Zhu et al., 2021) and prediction tools (Godara et al., 2007; Shaaban and Abdelwarith, 2020), rather than to assist design.

Another approach to pedestrian modelling has focused on crossing behaviours in midblock crossings (e.g. Sargoni and Manley, 2020; Zhuang and Wu, 2013): the crossing behaviour occurs in the context of moving vehicles without any crossing facility. Zhuang and Wu (2013) focused on road-crossing behaviours by modelling pedestrian crossing paths. In this model, they created three points which are one start position at one side of the road and two destination points on the other side of the road. Through this approach, they aimed to generate and evaluate the pattern of paths. However, this again limits the flexibility of choosing where to cross for pedestrians and creates a spatially restricted model of road crossing behaviour. Sargoni and Manley (2020) also focuses on the same topic of generating crossing paths, however they propose a framework in which pedestrian agents can decide on crossing location choice. This example focuses only on the choice of crossing location and does not include the interactions between vehicles, pedestrians and infrastructure.

Some of the other approaches included signalised crossing (e.g. Xi and Son, 2012). Modelling pedestrian behaviours in signalised crossing, Xi and Son (2012) created a model where pedestrians can enter the pedestrian crossing when the green light is on for them or wait on the pavement until the light is green. This illustrates a rule-following pedestrians and does not include the risk-taking pedestrians, which brings a limited approach to pedestrian crossing behaviour.

The last context for exploring pedestrian crossing behaviour is carried out in shared space and explores how pedestrian interactions with autonomous vehicles (AV) can be simulated (Prédhumeau et al., 2021; Yang et al., 2017). In the model constructed by Yang et al. (2017) explored a shared area where pedestrians can only avoid the slow moving vehicle when they are in close proximity. Prédhumeau et al., (2021) created a more detailed version of Yang et al.'s (2017) model. Their model included pedestrian danger and risk calculations which computed the type of interactions with AV and the response of pedestrians, respectively. The responses included accelerating to cross, slowing down to let the vehicle pass, stopping to let vehicle pass, stepping back and following group decisions. This example shows a range of interactions, however, they do not include signalised crossing and traffic light related behaviours.

In summary, the previous related work on pedestrian modelling has paid attention to different contexts of pedestrian crossing behaviours. Whilst some approached the decision-making prior crossing or in the presence of traffic lights, some looked into the pedestrian behaviours in other parts of the road (unmarked roadways) or shared space. These approaches depict various elements of pedestrian behavioural process such as risk assessment on gap acceptance, decision making about where to cross, what kind of path they choose, how they avoid collisions with vehicles by changing their route. However, they offer samples of various pedestrian behaviours in simulations. Therefore, they lack a cohesive structure to provide an overview of varied pedestrian behaviours and integration of these elements to model a deeper and richer pedestrian simulation. Therefore, there is an opportunity for creating a comprehensive and integrated pedestrian simulation to illustrate various behavioural modules during crossings that are identified at the end of Chapter 5.

I contend that agent-based modelling of pedestrians during their crossing can benefit more fully from a comprehensive infusion of realistic crossing behavioural process. Therefore, I present the case for, and proven usefulness of, a pedestrian agent-based model for experimenting with artificial agents in simulation. Whilst many existing approaches towards pedestrian simulations use video observation for calibration purposes (e.g. Crooks et al., 2015; Rivers et al., 2014), my approach in creating pedestrian simulation is sourced in real-world observation, modelling different levels of behavioural processes for perceiving and sorting the surroundings, mediating interactions and scheduling crossing activity based on the spatiotemporal context. In this chapter I address these issues by presenting realistic-behaving artificial pedestrian agents for experimentation.

This study aims to elaborate on the potential of using qualitative video observation to derive examples for agent-based models to frame complex behavioural processes of pedestrians during their street crossing period. In the next section, I first outline the potential software choices and which engine has been chosen for this research. Then in the following chapter, I will use the ODD protocol to explain the pedestrian simulation in detail.

Choice of Engine

For creating agent-based modelling simulation, I decided to use Unity3D (2021) game engine version 2020.3.18f1. Unity3D is a game engine which has been used in a variety of applications including agent-based modelling simulations (e.g. Huang et al., 2021; Wang et al., 2018). It has multiple features to manage the simulation: (1) spatial level such as 3D object locations, navigation areas, obstacle managements, (2) interface level, (3) coding level and (4) additional packages available on its Asset Store. In this research, I have used three additional packages from the Asset Store: (1) Sensor Toolkit (Micosmo, 2021), (2) Behaviour Designer (Opsive, 2021), and (3) Simple Traffic System (TurnTheGameOn, 2021). Sensor Toolkit is a system which helped to simulate vision for pedestrians. The Behaviour Designer tool helped to organise the behavioural requirements of pedestrians. The Simple Traffic System helped to operate cars and traffic lights. Additionally, navigation mesh class, which is a built-in module, has been used for the pathfinding system of pedestrians. The rest of my system (such as behavioural modules, decision systems etc.) was built by using built-in functionalities and extending them with the C# ("C-sharp") programming language.

Prior to using Unity3D, I initiated this study using NetLogo (Wilensky, 1999), an agent-based modelling environment that is widely adopted by ABM researchers and practitioners for their modelling process. There were a number of reasons for me to abandon this tool. First, this type of programming environment has not been used, to the best of my knowledge, in design practice. Therefore, I reached out to the Centre for Advanced Spatial Analysis in University College London and attended classes on the subject given by Dr Sarah Wise following the kind offer from Prof Micheal Batty. However, a combination of the UCU strikes and the ongoing pandemic prevented me from finishing the training. Subsequently, I attended the Humboldt State University summer modelling course given by Prof Steven F. Railsback and Prof Volker Grimm. During these lectures, they advised me to search for continued support throughout the rest of the study. After discussing the matter with the Technical Support at the Royal College of Art, I decided to take advantage of the support available for Unity3D.

Using agent-based modelling in Unity3D, I aimed to create a simulation tool that makes accessible to designers the process of simulating data for framing problems and testing potential solutions. The objective is that when a person with no computer engineering experience needs to use it for their research, they can easily tailor the inputs according to their observations or other methods they have used for data collection and they can have a simulation for their research. It is also possible to add new behavioural units through adding modules of codes or changing the environment through the spatial level.

In addition, since Unity3D is a game engine, it has more visual capabilities compared to more traditional ABM programming tools such as NetLogo. I have used these capabilities by modelling the environmental aspects, using its various camera and lighting options. However, I have not devoted a lot of attention to creating realistic visuals (such as high quality rendering) and animations (using an animated walking pedestrian). One reason for not adding these aspects (especially walking pedestrians) is that creating such features for an already complex behavioural model would create greater computational complexity and burden by slowing the process and creating errors (or bugs). Moreover, they could consume design and development time and introduce specifics and details that would complicate the model without providing any obvious benefit.

I had some experience using Unity3D before starting this PhD but, largely, I learnt these tools through my practical work in this study. This learning process was steep as the work presented here required extensive support. This support was provided by Dr Thomas Deacon, who is the Technical Collaborator on this simulation model. While the development of the model might have been difficult or not possible without Dr Deacon's support, the specification, the design and most of the model were my own, an integral part of the submission for this PhD. As the simulation process continued, the complexity of the model increased. To deal with this complexity, we have created mock-up scenes (test scenes) in order to test them modularly. These tests are exemplified in the Verification section called Simplifying the Environment. They aimed to scale down the environment and decrease the variables at any given time. However, this approach led to design decisions that introduced certain complexities in the code, including bugs. The model presented in this study is not intended to be ready for production. In other words, the model presented in the study was intended for rapid iterations to close the gap between simulation and video observations as discussed in the Methodology (Chapter 4). In the discussion section in this chapter, I propose some directions for bringing the model to production level.

Translating Qualitative Observational Data into Agent-Based Modelling

At the end of the previous chapter, I have constructed the behavioural models based on the feedback loops of the agents. In this section, I will use these behavioural models to build the agent-based model. This process is conducted by extracting the relevant information from the data by using the framework described by Zileli et al. (2021) (see Figure 6.1).

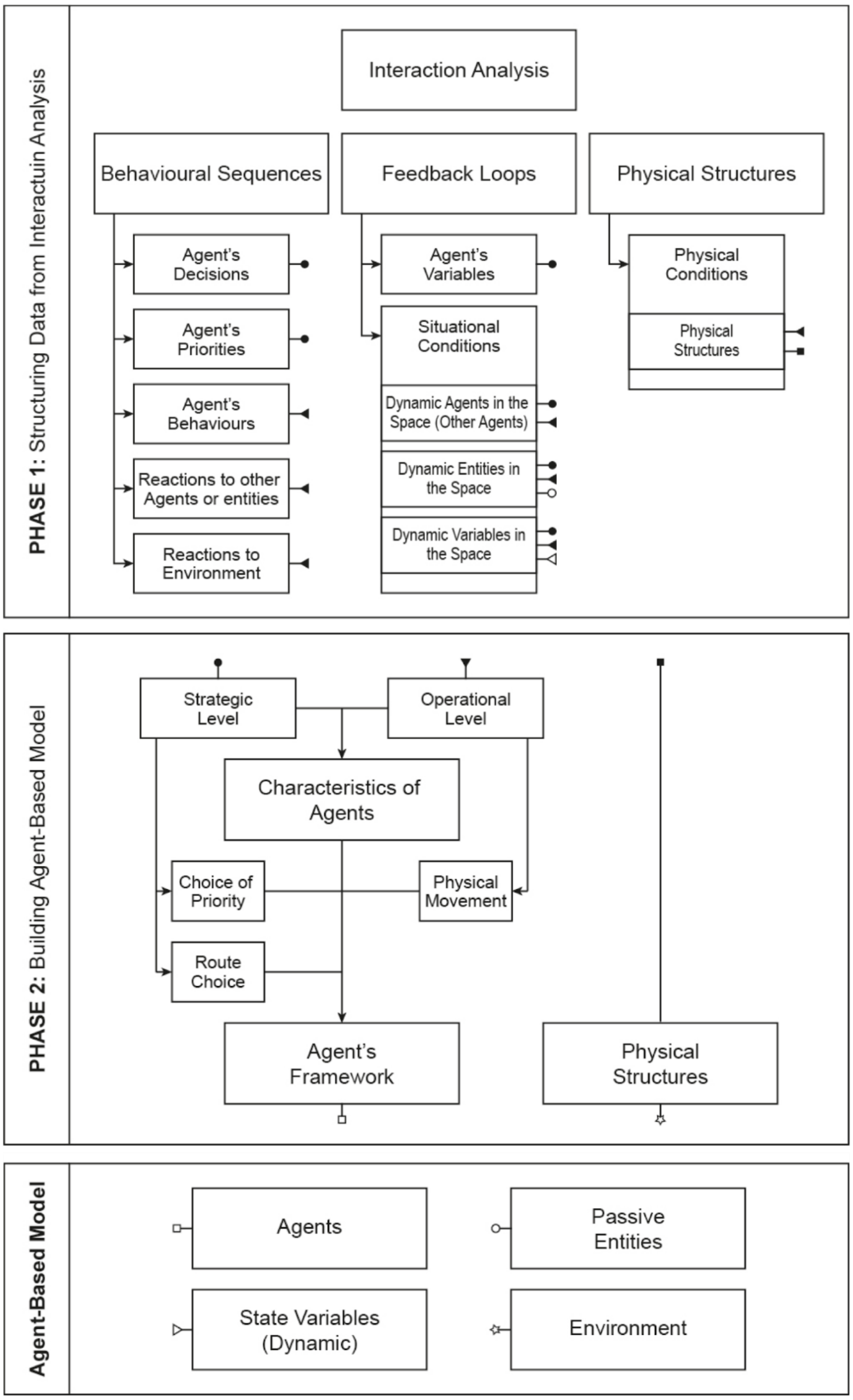


Figure 6.1. Framework that is used to translate the qualitative observational data into the agent-based model by Zileli et al. 2021.

The first two phases of the framework are described in Chapter 5 resulting in a number of modules for pedestrian agents and detailed analysis of the physical structures. When applying the agent's framework to the pedestrian simulation, I have used several processes for each module. Here, I will explain briefly how I have translated these behavioural modules. A more detailed description on how it is applied into the model can be found in the following section under *Submodels*.

Pedestrian agents' behavioural processes are designed to include four subsystems: (1) perception system, (2) memory system, (3) decision system, and (4) action system. Perception system handles the perception of vehicles *during their crossing* period through sensors and detection of the ground type (pavement, kerb, road, crossing) the pedestrian is on. Memory system stores the list of vehicles in long-distance range of the pedestrian in order to guide it *before crossing decisions are made*. The system stores data about potential hazards and the safe points pedestrians can escape if they are in danger during their crossing. Decision system manages pedestrian crossing decisions based on the hazard prediction and resolution and navigation behaviour of each class of pedestrians. Action system includes route planning, speed, and avoidance from other pedestrians.

Vehicle agents are controlled by a modular system that includes creating routes which cars will follow, generating the starting position of vehicles, managing the circulation of vehicles, perception of traffic lights, pedestrians and other vehicles and braking when there is a risk of a collision. Through the system, it is possible to have different speed limits for each vehicle, however, the speed limit can't be more than the speed limit of the route. The variables related to vehicles are further explained under the following section called *State Variables*.

Part of this system includes traffic lights manager. This controls sequencing of traffic light cycles and pedestrian traffic light cycles based on timers set for each sequence. Each traffic light cycle holds an array of traffic and pedestrian lights. Traffic lights are connected to the routes. Therefore, when the light is red for vehicles, the route transmits the 'stop' information to the vehicles. On the other hand, pedestrian traffic lights announce when the traffic light is green to the pedestrians who are waiting for the green light.

Physical structures include spatial layout of the environment such as pavement, road, pedestrian crossing, kerb, buildings, trees, street infrastructure such as lamps, traffic lights, bus stops. These structures were identified through the previous chapter using video recordings and photographs. While implementing these in the simulation, I took reference from these records and an online geographic database (OpenStreetMap). The test scene is influenced by the area of focus during the video observations.

Description of Pedestrian Simulation according to ODD Protocol

This section describes the agent-based model with the intention of providing information that is necessary to understand it and replicate the model that has been generated with it. The model descriptions follow the ODD (Overview, Design Concepts and Details) protocol for describing agent-based models (Grimm et al., 2006), as updated by Grimm et al. (2020). The overview section in this protocol includes purpose, entities, state variables and scales, and process and overscheduling. In this model, design concepts are of basic principles, adaptation, prediction, sensing, interaction and stochasticity. The details section includes initialisation and submodels. This model description sought to explain the agent-based model developed during this PhD in order to describe and ease model replication without being overly technical.

Purpose and Pattern

There is a growing interest in developing pedestrian behavioural framework and simulation models for pedestrian dynamic behaviour in various scenarios. However, as discussed earlier, there are only limited studies that look into the interactions of pedestrians with vehicles, streets, and other pedestrians based on the real environment.

This model aims to develop a pedestrian behaviour model by considering various real-world interaction processes (crossing methods) pedestrians' deploy at crossings. The purpose of this study is to model the real-world interaction process of pedestrians to understand their negotiation processes, inputs they rely on when they decide to cross, and variables that affect their decision. This representation of real world pedestrian processes aims to recreate the behaviours outlined at the end of the Chapter 5 through the qualitative observational study. These behaviours are (1) traffic light compliance behaviour, (2) explicit interaction with traffic light (3) long distance perception of traffic before crossing behaviour performed, (4) perceiving the potential dangers (5) acting according to the perceived dangers (6) crossing outside of the dedicated crossing area, (7) increasing the speed whilst crossing the road.

Furthermore, the model aims to create a space for conducting experiments in order to improve the design interventions (which will be explained further in Chapter 7). To guide this experimentation process, I have included four outputs in the visual interface: the number of three types of risk-taking behaviours that are defined as fleeing, stopping and re-pathing, and the number of pedestrian-vehicle crashes. The risk-taking behaviours are performed only when the pedestrian is on the road and in a close proximity with vehicles. The variables related proximity and further explanation of the risk-taking behaviours can be found further in the section under the *State Variables* and *Submodels*, respectively.

My agent-based model design followed an iterative process and was enhanced by simple behavioural rules that are presented above in order to produce more realistic patterns of pedestrian movements. These rules are informed by real pedestrian behaviour data and information about the physical environment through which the pedestrians are moving, as discussed in the previous sections.

The executable of the model, source code and all the data will be shared on Figshare to aid replication and experimentation. The model was developed with a deliberately modular architecture, to facilitate different types of pedestrian behaviours. Therefore, the model is regarded as a modelling framework that can be configured to produce a particular pedestrian model of interest, rather than a specific model in itself. This was intentional as the aim of the model is to produce a variety of pedestrian behaviours in order to experiment.

Entities, State Variable and Scales

This simulation addresses pedestrian agents and their interaction with vehicles when they cross the street. The goal of the pedestrian agents is to go to their end destination point (such as building, park, office etc.) without getting hit by vehicles. The destination points are regenerated once the pedestrian agent reaches their last destination. The route selection of pedestrians is dependent on the Navigation Mesh which is an embedded feature of Unity3d game engine. Navigation mesh generates polygons on the areas which are available to the pedestrian agents. The available areas for pedestrians are defined as road, kerb, crossing and pavement. The unavailable areas are defined as not walkable. The unavailability of an area occurs when it has structure on top of it such as buildings. Pedestrian agents currently choose their destinations randomly from a list of buildings assigned by the modeller. The path they have chosen can be affected by Navigation Mesh features (the cost of the path and availability of the path), obstacles on the path (vehicles, other pedestrians or spatial components) and the conflicts they have encountered (repathing meaning moving around the waiting vehicles and behind of moving vehicles).

Entities

There are five main entities in the model: (1) pedestrian agents, (2) vehicle agents, (3) controller (traffic lights), (4) environment, (5) spatial layout (road, pavement, kerb, pedestrian crossing and not walkable areas) (6) Reactive Entities. The pedestrian and vehicle agents are the dynamic entities in the model. The environmental elements (such as buildings, trees, lamps) and spatial layout are the static physical environment within which the agents act. The controller is the module which regulates the vehicle related street infrastructure- traffic lights and speed limits on the road. The reactive entities are the spatial entities with a system that detects which pedestrians are in unsafe situations and reacts to make that situation safer or warn the pedestrian about potential danger.

Pedestrian Agents: Pedestrian agents represent individuals who walk in the street environment to their destination point. Agents have a physical presence in the model, represented using a simplified capsule geometry with dimensions 1, 1, 2 (width/depth/height) with a rectangular prism to indicate the agent's direction (Figure 6.2). They have limited knowledge of the environment, not a holistic vision. They rely on synthetic vision based on Sensor Toolkit, a Unity Asset, that detects other entities and features in the specified distance and angle by the modeller. This "vision" is used for perceiving the short distance. The long-distance perception is controlled by another system, called Street Memory, which is scripted and explained further in the *Submodels* section. This system has a street perception that gives vehicle information to the pedestrian agent when it is approaching the road or crossing. The agent's behavioural process is modelled through four systems including perception, memory, decision and action (see Submodels for further detail). The behaviour of pedestrian agents shows variety in relation to their state variables which will be explained in the next section.

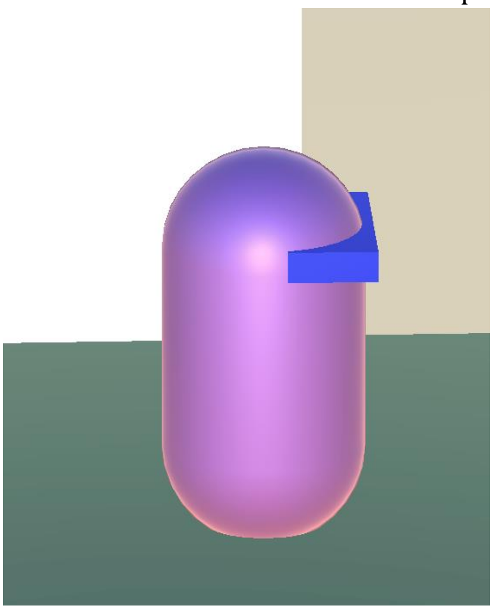


Figure 6.2. Pedestrian Agent Representation.

Vehicle Agents: Vehicle agents represent the cars who follow the road through simulation. They follow a waypoint-based path which they travel during the simulation. The waypoint route spawns the vehicles through a system called AITraffic Controller which is part of the asset named Simple Traffic System, an off-the shelf system for vehicles. Random Speed script controls their maximum and minimum speed. They have four sensors, two in the front and two in the back, to sense other pedestrians and vehicles. They also have a direction, called Drive Target.

Traffic Controller: Traffic controller represents the management of the vehicle related street infrastructure. The overarching system that includes the controller is called the Simple Traffic System in the simulation. This system is used because of its ease of use and to represent vehicles. In this model, the concern was not the level of reality of the cars, rather the aim was creating moving entities which can interact with pedestrian agents. Controller includes the traffic light manager and the traffic controller. Traffic light manager arranges the traffic light cycles. The traffic controller is responsible for spawning the vehicles from determined points and connecting the waypoint routes. The waypoint routes construct the vehicle paths. Each waypoint provides a speed limit. This speed limit cannot be exceeded by the vehicle. In the simulation, the speed limit represents the maximum real speed that a vehicle can achieve, that might be in excess of legal speed limits in the real street environment.

Environment: The environment is inspired by the actual street space. The street is designed through 3D mesh geometry using Autodesk Maya at an optimum level of detail to optimize the rendering and computation in 3D space (Figure 6.3). Environment represents the ground surface and obstacles on the surface. These obstacles can be buildings, lamps, trees and other areas with restrictions such as roundabouts. Some of the buildings also serve as destination points. The 3D model, which represents the environment is shown in Figure 6.3 Additionally, the environment includes invisible cubes. These cubes (or segments) cover the road area to collect data on the number of vehicles entering and exiting to the streets. The pedestrian agents then employ this information given by the segments in their long-distance perception of vehicles.

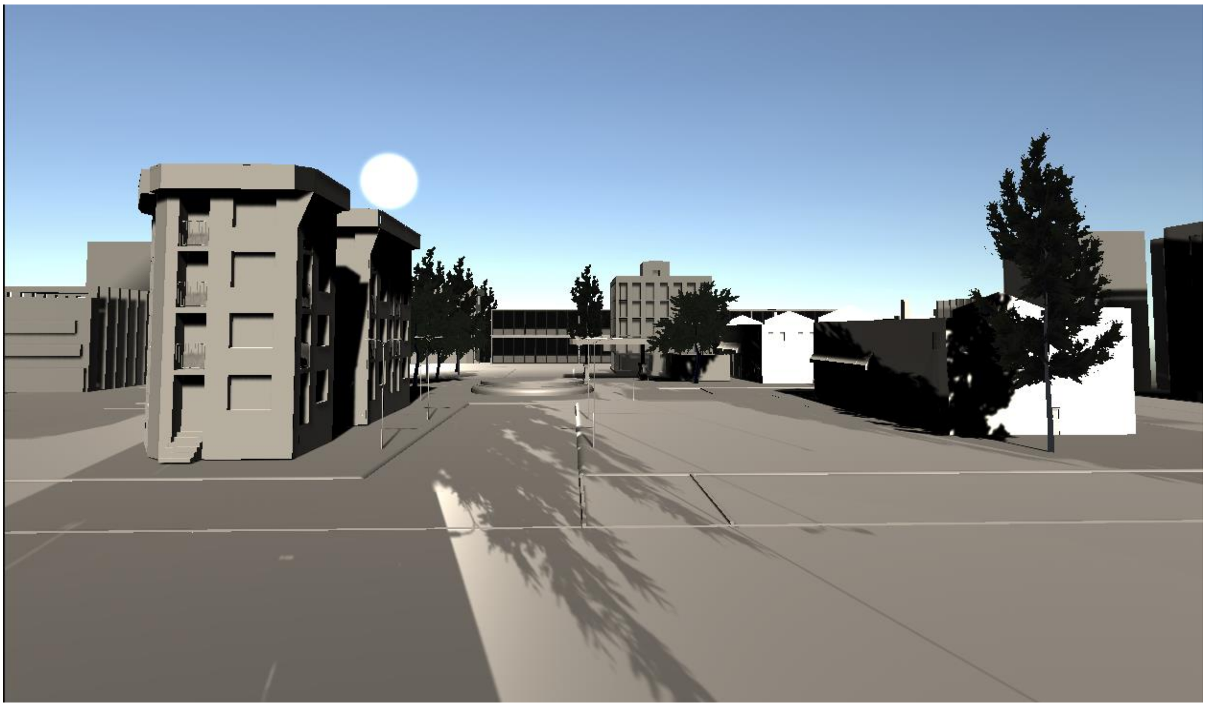


Figure 6.3. The 3D Model of the Environment.

Spatial Layout: The spatial layout is the entity on the system level, dependent on the Navigation Mesh class (a built-in feature in Unity3D) which is a part of the pedestrian navigation system in this model. In this model, the terrain is divided into five distinct types: pavement, pedestrian crossing, road, kerb and not walkable areas. Each terrain type exhibits different values in terms of "costs", determining which part of the ground is pavement, road and pedestrian crossing. Pavements (grey in Figure 6.4) are pedestrian agent-only areas and do not include vehicle agents. The cost of pavement is 1 per unit. Pedestrian crossings (purple in Figure 6.4) are navigable areas shared by vehicles and pedestrians that create a designated crossing area and might have traffic lights. The cost of pedestrian crossings is 3. Roads (pink in Figure 6.4) are navigable areas that are mainly populated by vehicles which pedestrians can use for crossing purposes. The cost of roads is 8. Kerb (light orange in Figure 6.4) is the edge of pavement which has a value of 2. Not walkable areas include the spaces occupied with static 3D mesh geometries. These are generally obstacles such as buildings, lamps, trees, or areas where pedestrians are not allowed, like a roundabout. The spatial layout of the environment is shown in Figure 6.4. Through these values, I aimed to create a more realistic pedestrian movement as they help to control pedestrian movement through creating a value-based system. For example, the highest value is the road area, therefore pedestrians avoid using the road if it does cost more than moving on the pavement or pedestrian crossing. However, in certain situations, they might choose to move through the road if it costs less. This generates various movement patterns where some pedestrians follow the dedicated areas, whilst others do not.

Figure 6.4. The 3D Spatial Layout of the Environment.

Reactive Entities: Reactive entities are the elements which respond to the pedestrian's actions during their crossing period. The response is dependent on the pedestrian's action such as the pedestrian positions or volume. These entities will be design interventions which will be explained in the next chapter.

State Variables

The simulation includes two kinds of agents: pedestrians and vehicles. Pedestrian agents are characterised by a number of variables such as speed, acceleration value, vision, long-distance vision. The vehicle agents include variables such as speed, deceleration, acceleration, front sensor length, side sensor length.

In the following Table 6.1 and 6.2 the pedestrian agent variables are described, respectively. Table 6.3 described the variables related to the traffic infrastructure. The first column presents the name of each variable. The state of the variable is shown in the second column. The dynamic state means that the variables vary throughout the simulation. The static state means the variables remain the same throughout the simulation. Then the meaning of the variable is described. The type of variable means how the variable is represented such as number, vector, integer etc.

Variable Name	Dynamic or Static	Variable Meaning	Type of the Variable
Pedestrian Density	Static	The number of pedestrians during the simulation	Number
Destination Point	Dynamic	The Destination Points for Pedestrians	Coordinate
Speed	Dynamic	Speed of the Pedestrians	Number
Acceleration	Dynamic	The maximum acceleration of agent as it follows the path	Number
Vision Range	Static	The radius of the agent that detects vehicles in close proximity (detection on road or crossing)	Number
Long Distance Vision Range	Static	The radius of the agent that detects vehicles in long distance (detection for before crossing)	Number
Update Interval	Static	The time agents take to process perceived vehicles	Number
Volume Tolerance	Static	The pedestrian threshold for the minimum distance between itself and vehicle to decide whether it is dangerous or not (for before crossing decision making)	Number
Future Position Time	Static	When checking to cross how many seconds further the agent should predict	Number
Emergency Stop Distance	Static	The pedestrian threshold for the minimum distance between itself and vehicle to decide which action to take to avoid from the vehicle	Number
Hazard Speed Sensitivity	Static	The maximum vehicle speed that a pedestrian considers dangerous to decide which action to take to avoid from the vehicle	Number
Obstacle Avoidance Priority	Static	Pedestrian agent’s priority when avoiding each other	Number

Table 6.1. The Pedestrian Agent Variables.

Variable Name	Dynamic or Static	Variable Meaning	Type of the Variable
Vehicle Density	Static	The number of vehicles during the simulation	Number
Speed	Dynamic	Speed of the Vehicle	Number
Deceleration Value	Dynamic	The amount of time vehicles take to decelerate	Number
Acceleration Value	Dynamic	The amount of time vehicles take to accelerate	Number
Front Sensor Length	Static	The length of front detection sensor	Number
Side Sensor Length	Static	The length of side sensor	Number
Stop Threshold	Static	Front detection sensor distance at which vehicle start braking	Number

Table 6.2. The Vehicle Agent Variables.

Variable Name	Dynamic or Static	Variable Meaning	Type of the Variable
Speed Limit	Static	Speed limit for each waypoint on the route	A number value
Traffic Lights	Dynamic	The colour of the traffic light	Colour (Green/Red)
Green Timer	Static	Green light Duration (in traffic light cycle)	Number
Yellow Timer	Static	Yellow light Duration (in traffic light cycle)	Number
Red Timer	Static	Red Light Duration (in traffic light cycle)	Number
Pedestrian Lights	Dynamic	The colour of the pedestrian light	Colour (Green/Red)
Starting Points of Vehicles	Static	Where does the vehicles spawn from	Coordinates

Table 6.3. The Traffic Controller.

Scales

The model's spatial extent is represented through 3d modelling inspired from the real environment. The environment is modelled accordingly to create a relationship between the video data and the simulated environment. The model's space is not toroidal (or wrapped) so the pedestrians can't exit from one edge and appear at the opposite one. One spatial unit in Unity3d corresponds to one metre.

The temporal scale is set as seconds based on real time. Time is represented as a discrete time-space. Agents update their location every second to reach their destinations. The temporal scale has two other scales – slower and faster options – through the buttons included in the interface.

Process Overview and Scheduling

The simulation processes in the model are planned as an integrated modular system that uses each step representing one second of time. In every time-step, a number of processes are activated; vehicle movement through Waypoint System (which is part of Simple Traffic System), pedestrian movement through NavMesh class, traffic light controller, ground check for pedestrian agents. Three events cause vehicle agents to wait which are pedestrian conflict, vehicle conflict or traffic light. Traffic light controllers activate red or green light for pedestrians and the opposite for vehicles every n time step. Pedestrians have a ground check feature. This feature is used for checking whether a pedestrian is going to cross or not by indicating where in the world the agent is positioned (pavement, kerb, road or crossing). If they are on the kerb, then they check which direction they are going and whether their next step would be road or crossing. If they are going to cross, they could use their long-distance vehicle detection system (which is in the Memory System in *Submodels* section), or check the lights.

Both vehicle and pedestrian agents are introduced into the environment at predetermined locations. Vehicle agents are introduced with spawn points which is a part of Simple Traffic System's feature. Once the simulation is started, vehicle agents follow the pre-planned route through waypoints. Pedestrian agents are located on random points on pavements. Once the simulation has initialised, a random destination point (from the destination list) is given to pedestrian agents. Through the NavMesh class, a built-in feature in Unity3d, the agent calculates its route, starts to move and engages with crossing, avoidance or waiting activities if necessary. When the agent reaches its destination, a new destination process is assigned. During the simulation, it operates based on the flowchart shown in Fig 6.5.

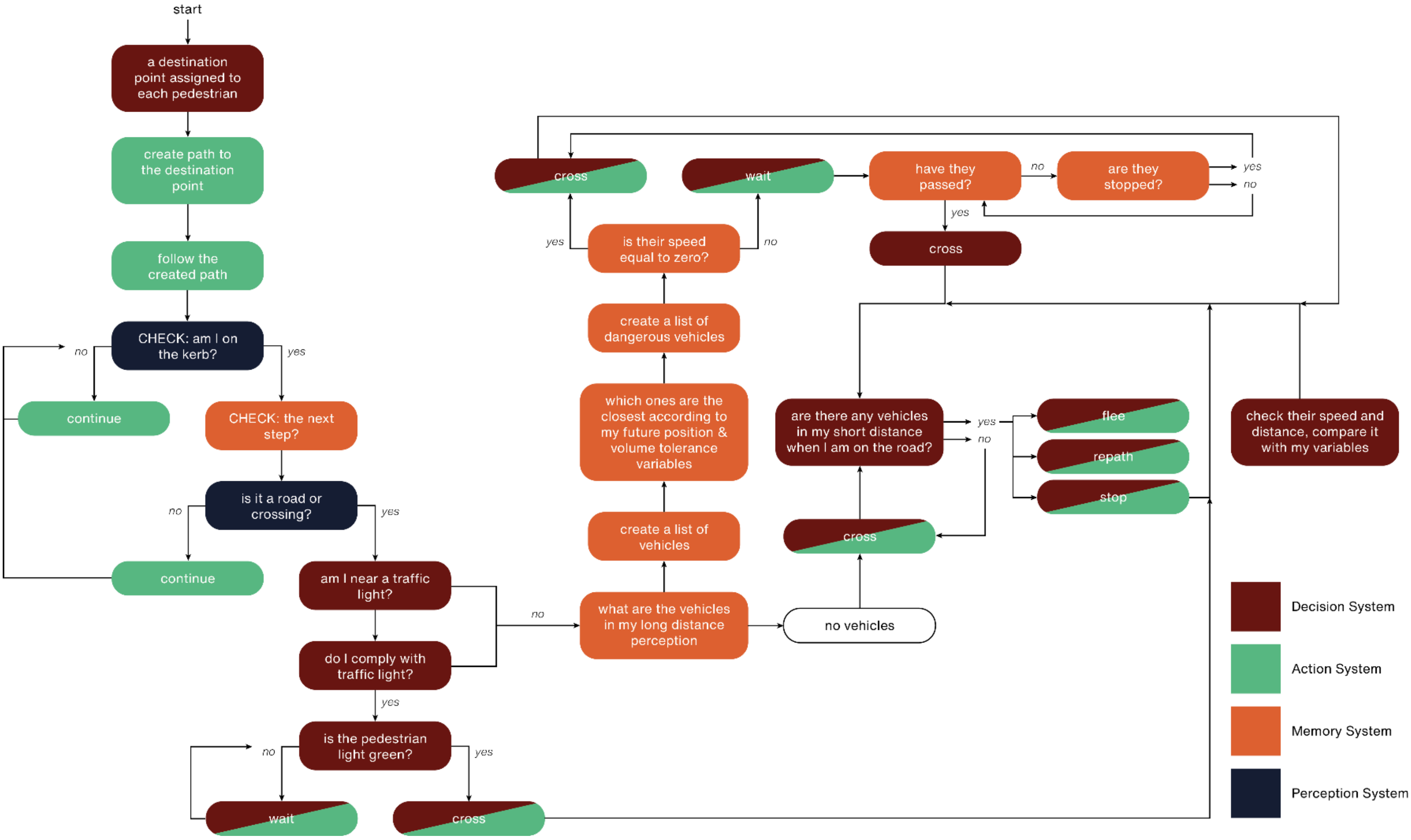


Figure 6.5. Flowchart showing the pedestrian logic in the simulation.

Design Concepts

The model integrates some of the design concepts from the ODD protocol of Grimm et al. (2006). Basic principles, adaptation, prediction, sensing, interaction and stochasticity are the most relevant of these. The purpose of the model is to observe the emergence of realistic patterns in pedestrian-vehicle-street interactions during the crossing period. In the context of this study, a realistic pattern is a simulated pattern identifiable in the video observation.

Basic Principles

In this agent-based model, the behavioural process of pedestrian agents is based on the principles and features of pedestrians seen in the street video recordings discussed in the previous chapter. The physical characteristics of street space are a simplified version of the observed area's characteristics. Pedestrian agents in the model are programmed to act by engaging in a number of processes such as sensing vehicles, traffic lights, understanding their position, direction, and the ground characteristics they are moving on (e.g. pavement, road, kerb, crossing). The crossing-related activities for pedestrian agents are planned through reactive principles that are based on connected events. For example, a part of their process is checking the ground in each step, when they are in the kerb area they also check their direction to understand their next step. If the next step enters the road or crossing, they activate the crossing protocol. This protocol can be waiting for pedestrian lights to turn green or crossing through their long-distance vehicle detection system.

Adaptation

The adaptation concept looks into the adaptive behaviours in the simulation by identifying the decisions agents make and the stimuli that enable this decision. In this simulation, the adaptive behaviours are explained in three sections: (1) adaptive behaviours of pedestrian agents, (2) adaptive behaviour of vehicle agents and (3) adaptive behaviour of design interventions. Adaptive behaviour of design interventions will be explained in the next chapter.

Pedestrian agents have a number of adaptive behaviours that allows them to decide to act according to the conditions around them. One of their adaptive behaviours is for long-term decision-making before they need to cross. This long-term planning aims to identify vehicles that are in conflict and according to their position, direction and speed when pedestrians are on the kerb and their next step predicted as the road. This behaviour uses two systems: memory system and decision system. Memory system keeps track of the potential vehicles in conflict. Decision system receives the vehicles in conflict and sends the information to its subsystems about whether there is a potential of hazard or not. If there is a hazard then the decision system stops the pedestrian agent. As a result, pedestrian agents make their crossing decision based on the vehicle presence and information around themselves.

One group of pedestrian agents only react to a green light during their crossing: if the pedestrian traffic light shows green, they cross the road. If it is red, they wait. They are named *rule-following* agents.

Another adaptive behaviour of pedestrians is their ability to react to potential conflicts on the road or crossings. These can be thought of as short-term emergency decisions they follow to avoid potential collisions when they are in very close proximity to a vehicle. Their decisions vary between stopping, repathing or fleeing to a safe space which is kerb or pavement. The variation depends on the pedestrian's position in the road, the distance between the vehicle and pedestrian, and the speed of the vehicle. These variations are influenced by the behaviours observed in the street.

The last adaptive behaviour of pedestrian agents is when they are in conflict with other pedestrians. Here, pedestrian agents need to make short term manoeuvres and adjust their route based on the presence of other pedestrians. This situation in the simulation is solved through adding a randomised avoidance priority to each pedestrian agent; whichever agent has the higher priority, has the right to continue its path, whilst the other with lower priority is forced to change its route.

Vehicles respond to the four dynamics in the street. These are speed limits on their paths, traffic lights, pedestrians and other vehicles. Their response to speed limits on their path is currently to not exceed the limits given. However, these could be altered to reflect the tendency of drivers to exceed the formal speed limit. Traffic lights are connected to the routes and when the traffic light is red the vehicle always stops. They additionally can stop when they detect pedestrians in front of them, however the stop threshold can change which creates dangerous driving behaviours. When there are other vehicles in front of them, they adjust their speed accordingly as well.

Prediction

In the model, only pedestrian agents are capable of prediction. They forecast two events: (1) whether they will enter a crossing or other part of the road on their next step, and (2) whether there will be any vehicles in conflict. One group of pedestrian agents (*rule-following* agents) only cross the road at pedestrian crossings. Therefore, they check only if there is a pedestrian crossing in their next step. On the other hand, the rest (*opportunistic* or *risk-taking* agents) perform this check for both non-crossing roadway and pedestrian crossings when they are on kerb. They employ a decision system to predict potential consequences of their decision to cross. They measure the speed, direction and distance of the vehicles. Based on this information, they can forecast where the car in conflict will be when they are crossing.

Sensing

Vehicles, pedestrians and the design interventions are all assumed to have sensing capabilities. Vehicles have three sensing mechanisms: (1) a short-range sensing system for detecting dynamic entities such as other vehicles and pedestrians, (2) monitoring the status of traffic lights, and (3) sensing the next point on their route. The distance that vehicles can perceive is determined by two values in the short distance sensing mechanism. These are the lengths of the front and side sensors, typically the front sensor of the vehicle senses 8 units and each side sensor senses up to 1 unit. The traffic lights are linked to the points along the vehicle's route. These points alert the vehicle about the presence of traffic lights, allowing the vehicle to either stop or continue moving. The sensing mechanism for the next point on their route has two purposes. First, it allows them to determine whether the next point is occupied by another vehicle. It also aids in identifying the characteristics of the next point, such as whether that point has a speed limit that requires adjusting or whether the next point is connected to a traffic light.

The sensing capabilities of pedestrian agents can identify five elements in the model: (1) long-distance sensing system, (2) short-distance sensing system, (3) traffic light monitoring system, (4) detection of other pedestrians and (5) spatial environment perception.

Long-distance sensing is a capability that all pedestrians have. However, some agents use it every time they cross, while others utilise it only in unsignalised pedestrian crossings. They can use this function to check the position of vehicles prior to crossing. It is dependent on the pedestrian's individual values, such as the range of distance that they can perceive and how frequently they check the vehicles. These variables are implemented to form different types of pedestrian behaviours such as dangerous pedestrian, cautious pedestrian etc.

Another technique that provides vehicle position and speed is the short distance sensing system. In comparison to the long-distance mechanism, short-distance perception is active only during the crossing phase, if pedestrians have vehicles around them. This system is not designed to predict anything; rather, it is designed to perceive the current vehicle status in order to avoid collisions. It is dependent on a range sensor, which is an individual value for perception radius.

Traffic lights can be detected by pedestrians who follow the regulations. When these pedestrians approach a signalised pedestrian crossing, they enter the traffic light detection range. The pedestrians who are actively listening are informed of the light's status.

Within a limited range, pedestrian agents can detect other pedestrians. They can only notice them if they are in a really close proximity as the pedestrians' avoidance from each other was not the focus of this simulation and required a different approach to navigation algorithm. Their obstacle avoidance priority variable receives a warning as a result of this. The pedestrian either gives way to the other agent or obtains priority to pass based on its obstacle avoidance priority.

Pedestrians are assumed to have an awareness of the environment that allows them to navigate in space. The navigation system uses this input for route-planning. Pedestrians also detect the type of ground (whether it's a pavement, a pedestrian crossing, a kerb, or a road) they are on and use that information to activate the necessary perception, action or decision systems.

A pedestrian sensing mechanism is included in the design intervention, which examines the distribution of pedestrian volume on different roads. This mechanism compares these roads and provides a selection of potential paths to vehicles. This will be further explained in the next chapter.

Interaction

In the model, pedestrian agents interact with other pedestrians, vehicles, infrastructure and the environment. Pedestrian agents interact directly with other pedestrians based on their avoidance priority, responding to their local movements. They decide to cross and move across the roads and crossings depending on the input provided by vehicle sensing systems (long and short term). Some pedestrians use traffic lights at signalised pedestrian crossings to mediate their encounters with vehicles. Traffic lights announce their state to these pedestrians as well as to vehicles.

The waypoint that is connected to the traffic lights receives the light's status and conveys it to the vehicles on that route. The interaction amongst the vehicles is established by the front sensor of each vehicle. This sensor informs the vehicle whether or not another vehicle is approaching the next point on its route, and hence whether or not it should modify its speed.

The front and side sensors also warn vehicles about the pedestrian presence. The vehicle brakes when pedestrians are detected within the stopping distance in the sensor's range. The vehicle route system is arranged in a way that different speed limits can be applied to the waypoints on routes. Therefore, vehicles adjust their speed in relation to the speed limits. Furthermore, the design intervention interacts with vehicles by conveying information to vehicles regarding route selection based on pedestrian volumes. This will be further discussed in the next chapter under *Designing an Intervention*.

Stochasticity

In the ODD protocol, stochasticity refers to how processes are characterised by assuming they are random or by utilising randomness to simulate variability in procedures that are not fundamental to the model (Grimm et al., 2010).

In pedestrian agents, stochasticity is employed in two ways. First, the model is stochastically initialised in a way that (1) each agent chooses their destination point randomly, (b) the obstacle avoidance radius for pedestrian to pedestrian interactions is generated randomly. These processes are initialised as random as they were not important in modelling pedestrian's crossing behaviours. In addition, these randomisations aimed to produce variability in pedestrian trajectories and their avoidance of each other, respectively. These initialisation methods are stochastic so that the model can be assumed to be random at the beginning of the simulation and that each model run provides different results.

Secondly, when a pedestrian agent reaches its destination point, it makes a random choice of new destination (but not completely random as a list of destination points set manually). This is stochastic because the details of movement and specifics of macro level route planning is not the focus of this model.

Stochasticity for vehicle process is produced through two different stages of simulation. During initialization, their maximum speed is randomised. During the simulation, their route selection when approaching a junction is also randomly selected (if the design intervention in Chapter 7 is not active).

Details

Details section of ODD includes initialisation and submodels. Initialisation aims to explain how many entities are created and what are the initial values of their state variables (Grimm et al., 2020). The submodels explain the rationale of the model in more detail about the overall process by dividing the system into parts.

Initialisation

During the initialisation, all pedestrians should be located on the pavement as they need to start from a safe space to their movement, all vehicles should be located on the road as starting points. The vehicle speeds, pedestrian speeds, pedestrian distribution, and pedestrian obstacle avoidance ratios are distributed randomly within a range which shows minimum and maximum numbers that can be given for the individual parameters. Pedestrian destination points are managed by a script called *BuildingManager* which keeps a list of potential destination points for pedestrians and distributes these points randomly amongst the agents. The list can be edited.

Submodels

Submodels include five systems. The first four systems, which are perception, decision, memory and action, constitute behavioural processes of pedestrian agents. The last one, the traffic system, manages vehicles and traffic lights in the scene.

Perception System: Perception system in pedestrian agents refers to a form of short-distance vision which reports the changing situations around the pedestrian agent. The perception system has three roles: ground detection, car detection, and checking lights.

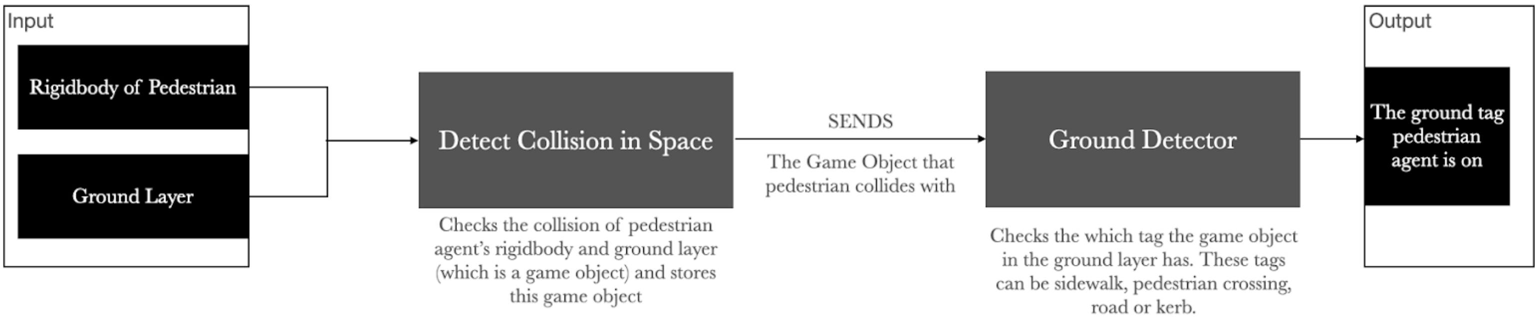


Figure 6.6. The Input-Output Flow of Ground Detection.

For ground detection, the code first checks which ground element the body of the pedestrian is intersecting with. This helps to identify the simulation object that pedestrians are on top of. Then, it looks into the specifics of this object to understand whether it is a pavement, pedestrian crossing, road or kerb. This information is updated every move to keep the agent informed. Figure 6.6 shows the information flow between different scripts during ground detection.

For detecting cars, the system uses a range sensor which acts as a vision for close distance. Through the range sensor, a pedestrian agent detects the cars inside of the area that the sensor covers. The sensor's range can be adjusted manually and differs amongst pedestrian agents between 10 and 15 units. It only detects vehicles and vehicles should have rigidbody (a built-in feature in Unity 3D that enables collision detection (Unity3D, 2021b)) in order to be detected. The sensor renews the data about vehicles every second, this also can be changed based on the pedestrian. However, in this simulation it is kept as 1 time step in all pedestrian agents.

Checking traffic lights occurs for pedestrians who obey the traffic lights. This is activated once pedestrian agents are inside of a volume near the traffic lights. When the agent is in the volume, the state of traffic lights (whether it is green or red for them) is announced to the pedestrian. After crossing the road, if a pedestrian enters a second volume near the traffic lights across the road, this is ignored as the pedestrian would be facing towards the pavement and continue its path. Therefore, there are four states for pedestrians in this section, *not observing* which means it is outside of the volume, *waiting* which means the light is red, *crossing* which means the light is green and *crossed* which means it is in the second volume.

<u>Memory System:</u> Memory system includes three sub-systems: (1) safety memory that records the last entered safe areas such as pavements and kerbs; (2) potential hazards for keeping track of the cars that can cause a hazard and (3) a long distance vehicle tracking system for making decisions about crossing or not.

Safety memory system gets the safe points for each pedestrian by checking their last exit and last entries into the colliders - invisible meshes that are set in the physical space. Then it checks the tag of these meshes to determine whether it is a pavement or not. If the last entry made was in pavement and the agent is not currently in a pavement mesh then the last entry space is defined as a safe point. Safety memory stores this safe point and the distance to this safe point.

Potential hazards uses the cars that are detected through the perception system (short distance) and long distance vehicle tracking system (the third sub-system of the memory system) to identify potential hazards. This system aims to update the list of cars that are sent by the short and long distance vehicle tracking systems. For the short distance vehicle tracking system, it updates the list through listening to the perception system. For long distance tracking systems, the vehicles that are potentially in conflict are updated based on the parameter called *update interval.* This parameter shows the input for how quickly an agent can process this information. This input in all agents is 1. However, the model analysis section will explore how variation of this parameter can affect the agent's collision avoidance and crossing decision processes.

The long distance vehicle tracking system is responsible for tracking vehicles just before pedestrians take the crossing decision. For this reason, this system checks first the pedestrians position and direction to calculate their next step. In terms of position, pedestrian agents need to be on kerb to trigger this system. In addition, the direction of pedestrians should be towards the road or crossing. If the agent is a rule-following pedestrian and it is on signalised crossing, then this system is deactivated for that agent. If all conditions are set, then the search for vehicles is activated. First, the pedestrian agent estimates its own future position on the road. Then it searches the vehicles in its range which is given as an input called *distanceCheckOuterBoundary.* This search lists the distance of the cars and their velocity. Then, this list was analysed to understand whether the car is dangerous. This analysis is based on (1) *futurePositionTimeAmount* – an individual parameter for how many seconds further the agent should predict, and (2) *volumeTolerance* – an individual parameter to determine how much distance is a danger for the agent.

<u>Decision System:</u> The decision system includes three subsystems: (1) hazard prediction, (2) hazard resolution, (3) organising the navigation behaviour by deciding traffic light compliance and assigning destinations.

Hazard prediction uses the short-distanced car list that *Potential Hazards* collected in the Memory System. It takes this list and predicts the future positions of the cars on the list. According to their future position, it defines whether the vehicle is dangerous or not. If the car is dangerous then it sends that to the *Hazard Resolution*. If the car is not dangerous, then the pedestrian continues its route.

Hazard resolution takes short-distance decisions on which actions to take when the pedestrian is on the road and when a dangerous vehicle is predicted in close proximity by the *Hazard Prediction*. According to the situation between the dangerous car and the pedestrian, *Hazard Resolution* includes three potential actions that pedestrians can take. These actions are taken by comparing the vehicle's speed and position with the pedestrian's threshold variables related to speed (*Hazard Speed Sensitivity*) and distance (*Emergency Stop Distance*). These pedestrian variables can be unique to each agent. If the car is very close and fast for the pedestrian agent, the pedestrian agent stops to wait for the vehicle to pass. If the car is close but not moving fast or stopped, then the pedestrian recreates its path around the car. If the car is far and its speed is high, the pedestrian increases its speed to reach a safe position such as the pavement. These actions are taken when pedestrians are on the road or crossing and there is a dangerous vehicle.

Navigation behaviour organisation is managed using a behaviour tree model, which is created with the Behaviour Designer Toolkit from the Asset Store (Opsive, 2021). In this simulation, the behaviour tree method is used to plan the execution of several systems. These systems included allocating destinations, organising the path, and checking the lights. Allocating destinations included choosing a random destination point from a list of buildings. This building list was created by the modeller. Path organisation consisted of determining the routes from the starting point to the designated destination point. Only agents who observed the traffic signals were required to check the lights. When the perception system identifies that the agent is near a traffic light and intends to cross, the checking lights system detects the status of the light and notifies the *Navigation System* in the *Action System*. As previously stated, the light condition includes red or green lights for pedestrians. If the light is red, the checking lights system informs the Navigation System to Wait. If the light is green, it informs the Navigation System to continue its path.

<u>Action System:</u> Action system includes three subsystems: (1) navigation system, (2) path calculation and (3) speed changer.

Navigation system is conducted by the embedded system in Unity3D called Navigation Mesh class (Unity3D, 2020). This system executes the actions that are decided by the decision system such as moving towards the destination point, waiting and continuing to move. In addition, the individual variables such as acceleration, speed and obstacle avoidance priority of the pedestrians are assigned through this system as well. Navigation system connects with the spatial layout in order to adjust its path through the road, pavement, crossings and kerb. This layout indicates pedestrian areas that are high cost and low cost (mentioned in the *Spatial Layout* subsection in *Entities*). These costs do not simply prevent them from moving onto high cost areas, rather, they enable the agent to make more informed decisions when navigating.

Path calculation is a system that aims to trigger the actions when pedestrians are in conflict with a vehicle. These actions differ according to short-distance and long-distance perception. In short distance perception, the data comes from the sensor system in the perception system. The actions the short distance perception triggers are flee, repath and stop as explained in *Hazard Resolution*. The long-distance perception is connected to the long distance vehicle tracking system in the Memory System. This system check is only triggered when the pedestrian is on the kerb and its next step is the road or crossing. If this is the case and a vehicle in conflict is detected in closer proximity than agent's *volumeTolerance,* then path calculation triggers 'stop' command for the agent. Pedestrians who follow traffic lights trigger 'long-distance stop' commands only when they are in an unsignalised crossing.

Speed changer is a system that adjusts the speed of pedestrians. This system is used by *Flee* action when the pedestrian needs to increase its speed. After this increase of speed, when the pedestrian reaches the pavement, its speed is readjusted to a normal one.

<u>Traffic System:</u> Traffic system is created through the Simple Traffic System (TurnTheGameOn, 2021) asset from the Unity3D Asset Store. This system is responsible for management of two entities: (1) vehicle system and (2) traffic light system. Vehicle system arranges navigation of vehicles, the variables of vehicles and distribution of vehicles. Traffic light system is responsible for the temporal arrangement of traffic lights and pedestrian lights, and the announcement of the condition of traffic and pedestrian lights to vehicles and pedestrians, respectively.

Model Evaluation

Model evaluation is one of the most challenging aspects of agent-based modelling (Crooks et al., 2019, p.244). The ability of an agent-based model to imitate the phenomenon of interest is one of the critical questions that is often asked of agent-based modellers. While there are no universally acknowledged methods for evaluating agent-based models, verification, calibration and validation are three of the most prevalent approaches (Crooks et al., 2019, p.244). The purpose of verification is to verify that the implemented model works as intended. This is a non-trivial process because the outcomes of agent-based modelling are not easily inspectable. Verification can be done through various methods, including code testing, simplifying environments, expected outcome alignment or docking (Crooks et al., 2019, pp.244-251). Calibration is another step for evaluation. The aim of calibration is to adjust the model's parameters in order to replicate the observed conditions. This can be achieved by qualitative calibration and quantitative calibration (Crooks et al., 2019, pp.251-260). Qualitative calibration relies on observed data whilst quantitative calibration relies on numerical values. Validation is performed through testing the model on some new data to avoid overfitting. In my PhD, the evaluations of the pedestrian simulation followed three steps which are: verification, calibration of the pedestrian agents and an initial validation.

Verification

By applying behaviours into the agent-based model, I have used the observed behavioural modules defined through the *Submodels*. These submodels are verified through the process by using the following two techniques: (1) Code Testing and (2) Simplifying the Environment.

<u>Code Testing:</u> Code testing was conducted by ensuring that no errors appeared during the execution period of the code. This process included searching for mistyped variables, correcting mathematical errors and checking the logical errors. These errors are further explored by creating simple environments in Unity3D to check whether the code modules are working as intended.

<u>Simplifying the Environment:</u> This technique is used to test the essential elements of the model alone and aims to understand whether they were working correctly. These tests were conducted by scaling down the features in the simulation. Some examples of these small sections can be future position testing, hazard resolution testing, or trajectory testing of the pedestrians.

Here, in Figure 6.7, I give an example of the test scenes that are used to test whether the behavioural module for pedestrians' next step prediction was working correctly. In this scene, first, the aim was to understand whether the pedestrian agent could recognise that its next step is on the road. Therefore, a representative capsule is created as a pedestrian. This capsule included next step prediction only. This is checked through adding gizmos (a tool for visual debugging). The blue circle shows the pedestrian's next step in 5 seconds from now according to its current speed.

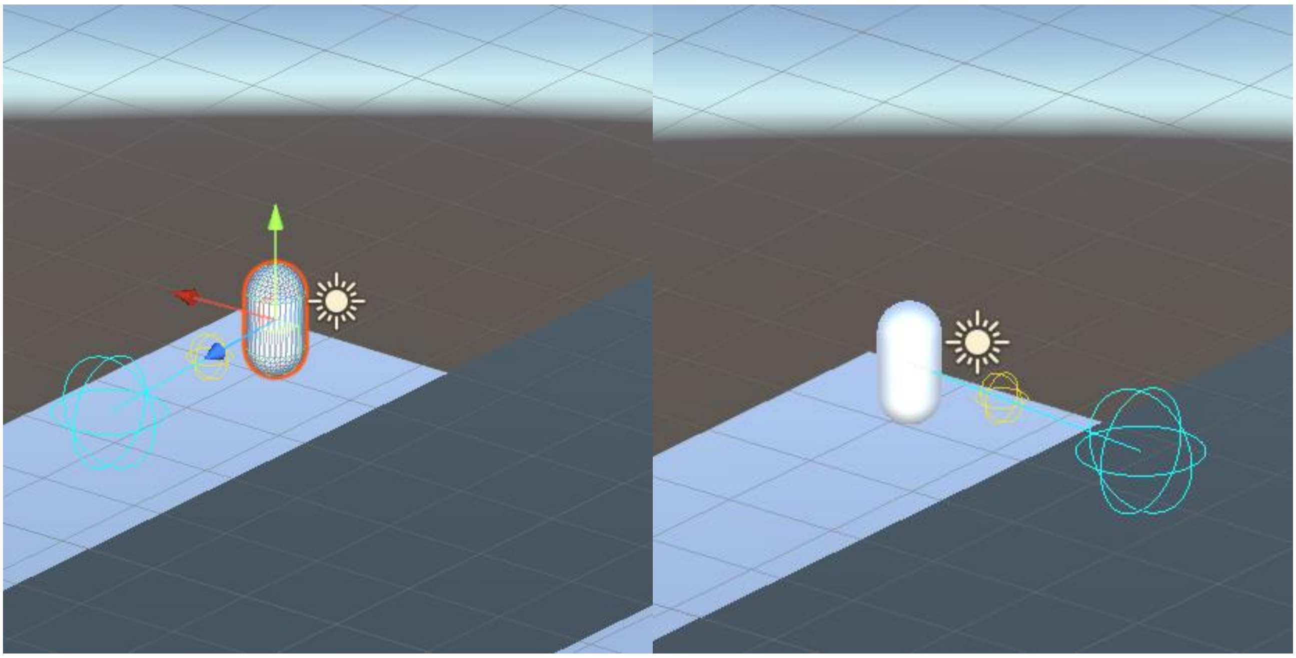


Figure 6.7. Showing the pedestrian agent's future position using a gizmo (blue sphere in the image). These two images illustrate the gizmo changing position according to the pedestrian's direction change.

The next feature to test in this environment was whether the pedestrian could identify the collision with the vehicle. This part first checked whether the pedestrian was able to identify the future position of the vehicle.

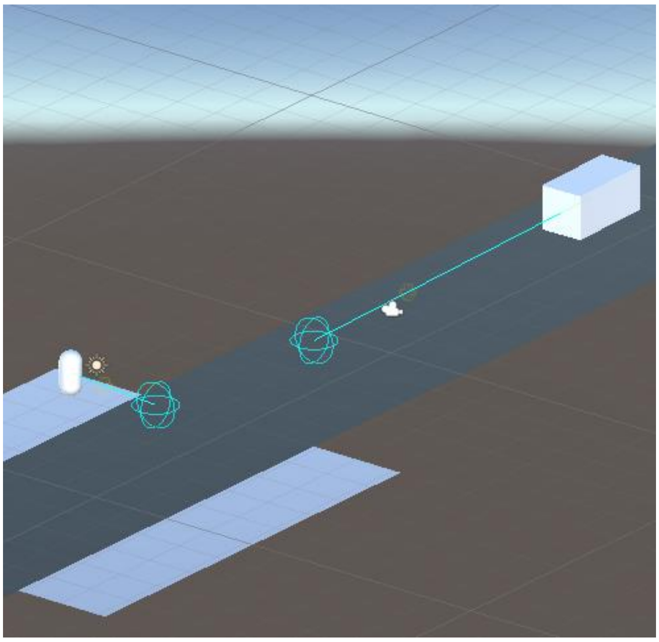


Figure 6.8. Showing the pedestrian agent's future position and vehicle agent's future position using a gizmo (blue sphere in the image).

This test scene also aimed to check whether the pedestrian could identify a conflict according to the future positions of itself and the vehicle. When there is a conflict, a gizmo is used to highlight that the pedestrian was able to identify the potential collision. This is highlighted in Figure 6.9 by a magenta coloured cubic form.

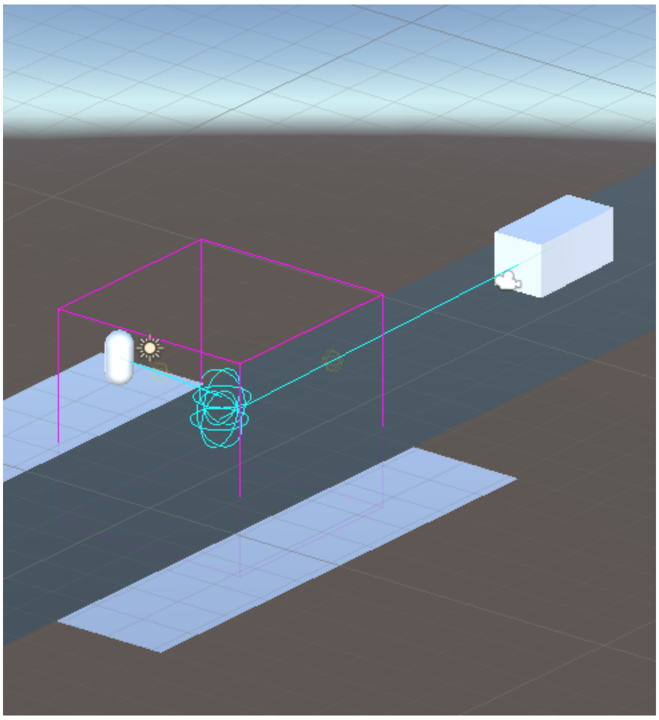


Figure 6.9. Showing pedestrian-vehicle conflict perceived by the pedestrian through magenta coloured cubicle form.

To summarise, this example illustrates one test scene that is created in the simulation and includes three processes (whether the pedestrian is correctly checking its future position, whether the pedestrian is correctly checking the vehicle's future position and whether the pedestrian is able to identify the future conflict) that are tested. These test scenes are conducted for each section of the submodel except the pre-built or in-built tools that are incorporated into the model.

Qualitative Calibration Through a Reflective Process

Through the study, my aim was to create a pedestrian simulation that can simulate the behaviours in the video observation. Qualitative calibration is applied by running the simulation in different parameters and comparing it with pedestrian examples from the video observations. When there are qualitative observations at hand, calibration can be used by estimating the related parameters that are unknown or cannot be observed (Crooks et al., 2019, p.251). This process aimed to match the behaviours of synthetic pedestrians to the real ones in the video. This type of validation is often called *face validation* (Crooks et al., 2019, p.251). This process was the first step for identifying the potential challenges and sensitivities that are going to be described further in the validation section.

This visual comparison aimed to analyse similarities and differences in the behavioural processes between the real pedestrians and pedestrian agents. The focus was comparing the real pedestrians who have been categorised through the previous chapter and the pedestrian agents who have been modelled through the simulation. Through these adjustments, a number of various pedestrian agent types are created.

In the following paragraphs, I have illustrated some of the example behaviours that are calibrated according to the video observations. These examples are (1) pedestrian crossing when the pedestrian light is green without interacting with the push button, (2) pedestrian interacting with push button and crossing when the pedestrian light is green, (3) pedestrian crossing when the pedestrian light is red and there is an availability on first lane on the road, (4) pedestrian crossing outside of the dedicated crossing area when the pedestrian light is red. In all examples, starting and destination points were arranged on each side of the road to capture the related behaviours.

The first example (in Figure 6.10) shows a real and artificial pedestrian crossing without interacting with the push button when the pedestrian light is showing green. The arrangement for the artificial pedestrian is made by enabling its compliance to the lights. In this example, the pedestrian's speed value was 3. Since they were following the traffic light, neither the real nor artificial pedestrian interacted with vehicles. Therefore, the values such as vision range, hazard speed sensitivity and emergency stop distance were not applicable to this example. Since this pedestrian crosses at a green pedestrian light when the vehicle flow is stopped, the variables related to long-distance vehicle perception (such as long-distance vision range, update interval, volume tolerance, future position time) are not included.

Figure 6.10. Pedestrian Crossing when the Pedestrian Light is Green without Interacting with Push Button.

In Figure 6.11, the example shows pedestrians who crossed the road by interacting with push button. This example excluded the same variables as the previous example for the same reasons: the only difference was going towards the pedestrian push button. This is achieved by activating an additional function that enables the synthetic agent to go towards push button when it is in the traffic light area.

Figure 6.11. Pedestrian Interacting with Push Button and Crossing when the Pedestrian Light is Green.

The next validation example is a pedestrian who ignores the crossing light. In Figure 6.12, the real pedestrian crossed when the pedestrian light was red and only checked the closest lane before crossing. In the synthetic agent, the future position projection for the agent made until the first lane, therefore, the synthetic agent checked only its future position as far as the first lane and identified potential conflicts in that lane. Since they did not check the potential conflicts in the second lane, when they were crossing the second lane, the artificial agent as well as the real one found a vehicle in conflict and stopped in the middle of the road. Through this interaction, the artificial pedestrian's calibrated variables included *vision range (for short distance conflicts), long distance vision range*, *future position time*, *emergency stop distance* and *hazard speed senstivity.* Vision range for short distance conflicts was 7 units. This was arranged so that the vehicle was not identified until it came certain proximity to the pedestrian. The long-distance vision value was 15 units. This allows the pedestrian to check the conflicts around her in the first lane however, not checking potential conflicts in the second lane. Future position time reinforced this by checking only first 3 time step of the route for potential conflicts. Update interval of the agent was 1 time step, which means she was quick at identifying the potential conflicts. Emergency stop distance variable is assigned as 4 units as the pedestrian did not stop until she was in the middle of the road. For this variable, I have tried 4, 5 and 6 units, and the closest result was when it was 4 units. Hazard speed sensitivity was used to repath behind the vehicle as the pedestrian in the video passed around the vehicle. Since the vehicle is stopped, repath is arranged as a function to go around the slowed down vehicle. The hazard speed sensitivity arranged as 6 units. This example illustrates how the validation process has been used iteratively to achieve a closer match of the synthetic agent's behaviour to that of the real pedestrian.

Figure 6.12. Pedestrian crossing when the pedestrian light is red and there is an availability on first lane.

In Figure 6.13, the example pedestrian in video was crossing outside of the dedicated area when the pedestrian light was showing red. Therefore, I tried to calibrate another pedestrian in order to create an artificial pedestrian agent that crosses outside of the crossing. However, when the pedestrian agent is alone in the scene and trying to cross, this behaviour occurs very rarely in the junction. Most often the artificial pedestrian will enter or cross through the edge of the crossing, if it is in the junction's side of the traffic light. Therefore, I have reduced the road's cost in this example to capture a pedestrian who was crossing outside of the dedicated crossing area near to the junction. However, I have not done this when I was validating the simulation, as in this route planning system the terrain costs for each agent are the same. The only way to create an intentional differentiation between agents about route planning is by preventing some rule following agents to cross in the middle of the road by disabling their access to the road. In this way those agents would use only the pavements, kerbs and crossings.

In the video recording of the Figure 6.13, the agent was crossing when there were no vehicles around. Therefore, I have increased certain values of the variables compare to the previous pedestrian example. These values were *long distance vision range* and *future position time*. This pedestrian's long distance vision range assigned as 10 units, so that he could be aware of any surrounding vehicles in close proximity. The future position time of the pedestrian agent was assigned as 8, so that it recognises any approaching vehicle as a potential conflict in both lanes.

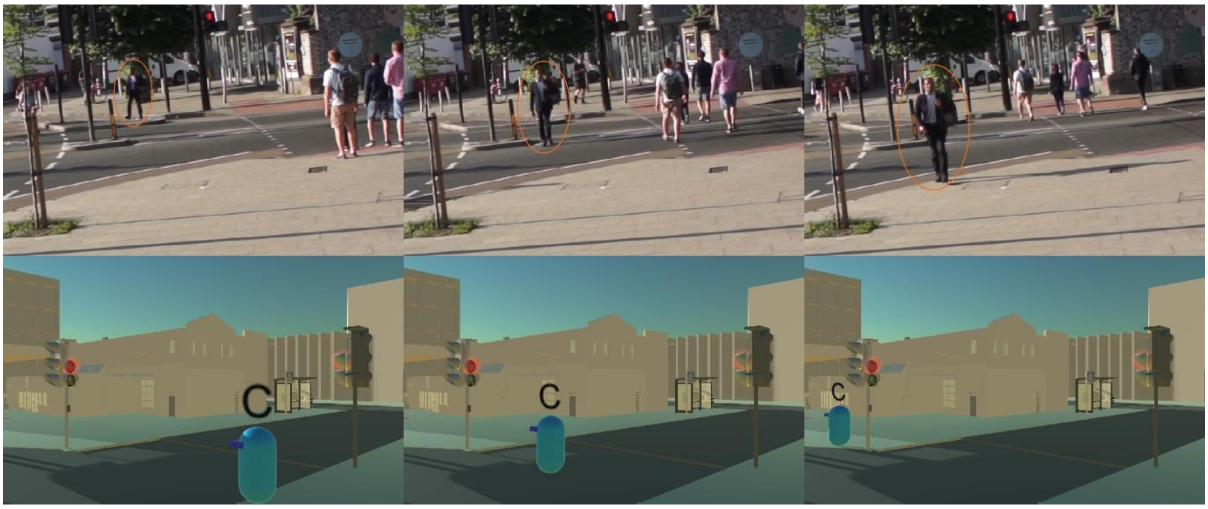


Figure 6.13. Pedestrian crossing in red pedestrian light outside of the dedicated crossing area.

For the further calibration of the model, two suggestions could be pursued: (1) following a 'companion modelling' approach by conducting an interview with potential stakeholders or pedestrians and increasing the richness of the simulation, (2) collecting quantitative data in order to increase the accuracy of the parameters. The first was beyond the scope of this research; the second is described next.

Quantitative Monitoring of Behaviours Through the Information Interface

During the calibration stage, I have also incorporated an interface for monitoring and counting risk-taking behaviours and pedestrian hits (Figure 6.14). This interface is accompanied by a camera function that focuses on these events as they occur. Risk-taking behaviours included three different types of action: (1) stopping, (2) fleeing and (3) repathing. Pedestrian hits calculate the number of collisions between vehicles and pedestrians. These measures were added for two purposes: (1) analysing different pedestrian risk-taking behaviours in detail and how parameter variations affect the behaviour of pedestrians and (2) making a comparison during the experimentation of the design intervention, which will be explained in the next section.

Analysing different pedestrian risk-taking behaviours in detail was necessary to create parameters representing each behaviour at the right moment. For example, when a vehicle is approaching fast and the pedestrian is in its path, the pedestrian should move fast to avoid the vehicle, rather than stopping. These fine-tuning behaviours are made by monitoring and observing when pedestrian agents trigger one of these behaviours. In addition, it is also possible to create different maximum speeds to represent slow-moving pedestrians for fleeing. This is also explored through this interface.

This interface was especially useful when multiple pedestrians were in the scene to understand how safe the environment is and how various pedestrian characteristics are in the scene. This interface, for example, helped to identify that if pedestrians were not showing any risk-taking behaviours, then the composition of the pedestrian characteristics of the surroundings (such as traffic light timings, vehicle speeds) should change.

Preliminary Validation and Future Steps:

During the calibration stage, I have included the starting and destination points as specific places and compared the behaviours between those points. On validation, starting and destination points of the pedestrians are randomised. Their speeds were also varied as well. Apart from these measures, for most of the pedestrians the variables related to long distance crossing decisions and short distance risk taking decisions was kept according to the calibrated pedestrian characteristics given in the previous section. Some characteristics, for example pedestrians who cross when the pedestrian light is green, needed to be adjusted for the cases where they need to cross an unsignalised crossing or road. These variables are adjusted through randomisation as it was not possible to know how this group would behave at unsignalised crossings from the observation study in the previous chapter. In addition, other attributes, such as cautious pedestrian and dangerous pedestrian characteristics, are created by arranging the variables related to long distance crossing and short distance risk-taking decisions. This is applied by changing the long distance vision range, update interval, volume tolerance, future position time (for long distance crossing decisions) and vision range, emergency stop distance and hazard speed sensitivity (for short distance risk taking decisions). Furthermore, if a researcher discovers further different risk-taking levels, they can change these parameters accordingly to create the behaviours under observation.

One behaviour that emerged by using numerous different pedestrians in the virtual scene is the *following behaviour*. When several artificial pedestrians are in the same area to cross (such as a crossing area when the pedestrian light is red), it is observed sometimes a pedestrian agent started to cross and another followed it. This seems to be because of their different information processing times (update interval variable) or changing situations in the street context, such as changing vehicle speed. For example, a synthetic pedestrian started to cross, and a vehicle agent stopped to give way, this can trigger the other pedestrian's crossing decision as the closest vehicle's speed is zero.

Through the model, there were certain challenges which originated from building the system through iterations and using in-built or pre-built systems. The first challenge was the high-level complexity of the system as a result of building the behavioural modules as interconnected. This sometimes slowed the system by causing errors in pedestrian agent's behaviours. This error often was stopping a pedestrian or changing its destination point to its current destination. These errors were solved as much as possible with the given architecture of the model. Despite these occasional difficulties, the simulation works when run on a sufficiently powerful computer. However, future research should focus on using behavioural modules such as I have described and building them as a finite state machine. This computation model has a finite number of states, and transitions between these states and actions can be implemented as sequential logic, allowing certain actions to be locked when they are not used and unlocked when certain actions are performed. This would expedite pedestrians' behaviours by closing some systems when they are not used and initialising them when they need to be used. This differs with my computation model, which constantly monitors situations and triggers actions.

It is important to note that my aim was not to reproduce the trajectories of pedestrians or build a high-level trajectory planning algorithm as the primary focus in this simulation was creating diverse pedestrian crossing behaviours. Therefore, trajectories represented in the simulation relied on a pre-built system. This caused some challenges in certain route planning issues when pedestrians were navigating in a crowded environments or in high-level of traffic. This issue has occurred in two different behaviours for pedestrians in two specific situations. One was when the pedestrians needed to avoid each other. This avoidance behaviour was managed through the obstacle avoidance priority variable. This was a simple, but limited, way to address the problem of pedestrians colliding. Another issue arose with the repathing behaviour. I have observed that it was challenging for the pedestrian agents to repath when the vehicles were directly cutting their way and they need to make a major turn in their route to pass the stopped vehicles. Both of these problems could be solved by using a different navigation system such as A* algorithm or another more sophisticated trajectory planning algorithm such as Liu et al. (2014), Vizzari et al. (2020) or Johora et al. (2020).

Another limitation in the simulation was the pre-built vehicle system (Simple Traffic System). Similarly to the route-planning system, a vehicle system was not the focus of this agent-based model. They were merely functional support for creating the dynamics in the virtual environment, so I have used a pre-built system. However, this system was sensitive to certain variables. For example, turning the corners of the road without causing an incident needed fine-tuning of speed limits in order to prevent them crashing each other. Further development on the simulation would preferably incorporate a more sophisticated traffic system than the pre-built one used here. Some examples could be combining the CARLA simulator (CARLA, 2021), vehicle simulation created by Garzón and Spalanzani (2018) and Torabi et al. (2018).

Discussion

As pointed out in the literature section of this chapter, previously different aspects of pedestrian mobility on the street have been addressed by others. However, through the literature, a comprehensive behavioural model of pedestrian interactions during their crossing period was lacking. In this pedestrian agent-based simulation, I aimed to create a comprehensive behavioural model of pedestrians by addressing their interactions with vehicles and street infrastructure (traffic lights and pedestrian crossings). Through the study, my aim was to recreate pedestrian agents that show a variety of behaviours and responses to their situational context based on the video observation study. I have achieved this, first by analysing the stimulus and responses in pedestrian decision-making in the video observation study (Chapter 6) and using it to inform the agent-based simulation for the depicted scene. The relationship between the two techniques helped to identify various behaviours, their relationship and the course of events. The rich data coming from interaction analysis helped build the agent-based model. As I have described, consistency between the video and the simulation was achieved in three ways: (1) through the framework built while translating the observations into the simulation, (2) the reflective relationship between the two techniques and (3) the qualitative evaluation just described.

One of the takeaways from this study is the complexity and challenges of modelling pedestrian movements and interactions which perhaps partly explains the reason why this kind of comprehensive model of pedestrians has not been addressed previously. As pedestrians have individual agency in acting and interacting with vehicle flow in the street, factoring and representing even a subset of the possibilities that an agent can act upon requires multiple processes (as explained in the *Submodels* subsection). This complexity of processes can reveal how the reactive pedestrian agents respond and interact with different environmental and situational conditions through their movement. However, it also complicates the evaluation of the pedestrian agent behaviours during the simulation as the potential causes for a behaviour can lie in multiple places inside of the agent's behavioural system. This particularly complicates the analysis and calibration of the model.

Future research about such models can include making more dynamic characteristics for pedestrian agents who change their behavioural process from rule following into taking risks through their path. This can include a temporal element for the pedestrian agent's characteristics. One example can be giving agents a certain time to be at their destination point and based on that timeline their behaviours (such as risk-taking behaviours), decisions (such as route planning and crossing decisions) and speed would change. As noted, an aspect that must be addressed in order to improve the model is the transition of the behavioural modules to a different model of computation, such as a finite-state machine. Another interesting next step would be combining this model with a more advanced pedestrian route planning algorithm as pointed out in the *Preliminary Validation* and *Future Steps* section. Another improvement would be combining this pedestrian model with a more elaborate vehicle system where vehicle behaviours are diversified and are less sensitive, as previously mentioned.

Chapter 7 Designing an Intervention

Introduction

Through the previous study, I created an agent-based model for simulating pedestrian behaviours in order to understand and create an experimentation space for design interventions. The aim was to explore the street environment as a pedestrian ecology that shows the interaction between pedestrians and their surroundings including vehicles, street environment and other pedestrians. This was achieved by combining a number of behavioural modules within the simulation, including long- and short-distance perception of vehicles and other pedestrian actions. Through using these modules, I succeeded in creating different types of pedestrian behaviours such as opportunistic pedestrian behaviour, rule-following pedestrian behaviour and eager pedestrian behaviours. Furthermore, in some situations, a pedestrian behaviour has emerged: the follower pedestrian behaviour who follows other pedestrian's decisions. Using these representations of pedestrian behaviours helped to show the interconnection between actions and their contextuality whilst investigating the process of how these actions can be built in a virtual environment.

As explained previously, the goal of using an agent-based simulation model is not just to explore real-world pedestrian patterns but also to experiment with potential design interventions that might eventually be implemented in the real world. Agent-based models provide a suitable toolset for both these aims by representing various movements and behaviours using an agent to represent each individual (Filomena and Verstegen, 2018). The relationships between these agents provide insights at the interaction level by forming real-world patterns. Through the studies described so far in this thesis, the agent-based model was used to understand the context and complexity of pedestrian interactions and generate mechanisms by recreating their individual behaviours and actions.

Now, building on these previous studies, the simulation tool is used in order to aid the experimentation process for designing pedestrian-centric and dynamic interventions. Using agent-based modelling for experimentation purposes is useful due to its flexibility. Agent based models feature numbers of parameters which enables them to generate more data than other models (Polhill et al., 2007). Through these parameters, agent-based simulation allows us to change conditions, agent characteristics and present a space to experiment different applications in order to examine possible outcomes and behavioural processes (Chaturvedi et al., 2005). By producing an environment that is open to modification and flexible (Crooks et al.,

2008) to support different scenarios, agent-based modelling allows us to generate different scenarios, scales or areas of application hence presents a space for experimentation.

To demonstrate the experimentation process, I used the simulation tool to implement an example intervention so I can discuss its design process and possible outcomes that give insight for the proof of concept. The initial purpose of this experimentation is to explore the process of incorporating the intervention into the simulation tool by translating it into the virtual environment. Then, the study aims to depict the simulation tool's potential for recommending guidelines on practice by experimenting with it within different scales (temporal and spatial). Understanding the issues that arise during the virtual experimentation phase seeks to contribute to refining the intervention's initial design through a reflective and feedback-oriented approach. Rather than employing agent-based modelling as a tool for prediction or forecasting, this approach is intended to contribute to the interpretation of how simulations can be used to define and conceptualise the intervention in consideration.

One popular approach to consider transferring technology is to measure technology readiness levels (TRL) (Chukhray et al., 2020). NASA developed technology readiness levels to objectively assess the maturity of technologies (Mankins, 1995). Its goal is to allow for consistent, uniform discussion of technical maturity across various forms of technology (Mankins, 1995). The nine levels of TRL are usually presented as follows: (1) basic principles, (2) formulating the application, (3) proof of concept, (4) laboratory experiment, (5) pilot experiment, (6) large scale experiment, (7) demonstrating in an operational environment, (8) technology approval through test and demonstration and (9) technology approval through successful mission operations (House of Commons, 2011). According to Chukhray et al. (2020), simulation and games can facilitate information on the interaction and behaviour of people depicted in a specific environment in order to increase the project's creative potential. In this study, by employing simulation to reflect on the intervention, I intend to address the first two levels of the technology readiness levels to move the intervention from an idea into a proof of concept.

In other studies, agent-based modelling is used to investigate more static interventions than those I am interested in. For example, one example of use of agent-based modelling is to develop evacuation plans for different sites and events such as flood events in cities in order to develop different evacuation strategies (Medina et al., 2016), or student evacuation behaviours in a classroom to evaluate different planning schemes for classrooms (Liu et al., 2016), or emergency evacuation for a building to evaluate the architectural design (Ha and Lykotrafitis, 2012). While in these investigations the agents of course are dynamic, the interventions to which they respond are static. Another example is using agent-based modelling for spatial design and architectural practice in order to support the decisions made for urban or architectural spaces (e.g. Esposito and Abbattista, 2020; Sengupta and Bennett, 2003). These examples show agent-based modelling simulations most often used to evaluate different variations of plans, layouts or spatial decisions that are intended eventually to remain unchanged, and which do not alter during the running of the simulation.

In this research, on the other hand, my aim is to explore dynamic interventions that are able to sense and respond to what they have sensed. The dynamic approach brings a temporal dimension to the street during the intervention phase. This can be explored with transient interventions in the environment, such as short term road closures and movable structures like parklets and cones, discussed in Chapter 2. The taxonomic review in the same chapter also located a few existing examples in the dynamic intervention section, revealing proof-of-concepts (such as smart surface, smart crossing, automated push button etc.) which generally are in need of a certain level of pedestrian awareness to function. By pedestrian awareness, I mean the system detects some aspects of pedestrian-related localised changes in the environment using sensory mechanisms. It was also clear that they need an interface to communicate with pedestrians and vehicles in order to make evident the outcome of what they have sensed.

In the next section, I will be explaining the requirements that need to be decided during the implementation of the dynamic intervention into the virtual environment. These include the information that the intervention senses, the functions of the intervention according to what they have sensed, the temporal timeline of the intervention and the interface for the intervention in the virtual environment.

Requirements For the Intervention

The first requirement for a pedestrian-centric dynamic intervention is to be aware of pedestrians, in order to initiate a resultant process or action. The dynamic intervention should at least sense some aspect of pedestrians (though it might in principle also be sensitive to other changes in its environment). This aspect may be changes as pragmatic as pedestrian speed, position and volume of pedestrians. It might also be more intuitive, such as inferring the intention of pedestrians, as companies such as Humanising Autonomy (2021) aim to achieve. In this study, I will be focusing on the immediate pragmatic aspects that my research has focused on so far.

After sensed data is processed, the intervention would need to intervene and alter the environment in favour of pedestrians. To be dynamic and responsive, the intervention must clearly have at least two alternative responses, that differ according to the information derived from the sensing: they can be variable responses based on the information, or they can be an on/off response. One way to define how many responses one would need is by specifying the amount of differentiation in the sensed information and the way to evaluate them. For example, if the intervention focuses on sensing pedestrians on the kerb and the vehicles near them, the intervention's aim could be to slow down the vehicles when they are too close to the pedestrian. This slowing down response could be triggered at a certain distance according to the vehicle's speed and distance from the pedestrian. If the vehicle is too close, the response can aim to stop the vehicle; if it is moderately far, the response can aim to slow down the vehicle, and if they are far away, the intervention will not change anything; therefore, it would be off. As a result, this would give three responses according to the collected information.

Another aspect of the intervention that needs consideration is how often the intervention should sense and respond to the changes happening in the environment. Deciding on the temporal dimension is useful to prevent unnecessary data collection, processing and data accumulation. The temporality depends on the purpose of the intervention, what the intervention senses, and the intervention's responses. For instance, if the intervention is similar to the previous example, in close proximity, sensing the conditions every second or every two seconds could be a wise strategy. However, if an intervention has a more extended response period, such as increased street lighting to aid visibility of pedestrians, it could sense every five minutes. One of the benefits of using simulation tools to experiment is that it can help decide the intervention's temporality. Therefore, at the beginning of virtual testing, it would be sufficient to have some initial concept about the temporal dimension of the intervention and then refine this through experimentation.

The other requirement for the intervention is some kind of informative output. For example, a visual aspect of the intervention in the virtual environment can indicate that the intervention has been triggered. Through this indication, it informs the observer or the researcher which function triggered it and when it was triggered. In the actual real world environment, on the other hand, the role of the informative output is as a communication tool to inform pedestrians and vehicles. In this study, I will show how I used the visual aspect in a virtual environment in order to inform the observer and researcher. Then, I will explain how these could be transferred into proof-of-concept for a real environment.

The Purpose and Position of the Study

This study aims to address the research question by depicting an example of pedestrian-centric dynamic intervention. Through this example, the study exploits the taxonomical and conceptual reviews that have been set out in Chapters 2 and 3, respectively. The taxonomical review located the existing examples of interventions in the spatial and temporal frame through the lenses of permeability and dynamic approach, revealing the lack of existing interventions in the area of dynamic and increased permeability.

The dynamic concept of the intervention was further explored through the literature in Chapter 3, by positioning it within the concepts of complexity, adaptation and responsiveness. Complexity was used to explore the interdependencies, interactions and behaviours of pedestrians that shape street mobility. This exploration helped to recognise conflicts and the situations occurring around pedestrians. Through introducing the idea of adaptation, I developed this recognition of conflicts one step further, aiming to reduce conflicts based on my new understanding about pedestrians. Responsiveness helps to avoid conflicts by using a feedback mechanism that recognises the certain aspects of pedestrians in order to actuate the assigned action.

This chapter attempts to shape the intervention in the light of the concepts that have been introduced, by using the simulation tool. I will first describe an intervention that is to be experimented with and explain why certain decisions around the interventions have been made. Then I will explain the simulation experiments through scenario building in order to compare the effect of the intervention. This section will also include a discussion of how the intervention can be improved. A following section offers reflections on the potential demonstration of the intervention. To conclude the chapter, I summarise the role of dynamic pedestrian-centric intervention and the experimentation process.

Description of the Intervention

Whilst choosing this example, I address a number of concepts in order to create a refreshed understanding of intervening into the street. First is the pedestrian-centric approach. This focuses on considering the pedestrian's temporary relationships in space and recognising the specified aspects such as their positions, volume, speed etc. Therefore, as I have outlined before, the first quality of the intervention is sensing selected features of pedestrians. Basing the intervention on pedestrian-related features is intended to impact two aspects of pedestrian mobility: (1) convenience and (2) safety.

Convenience in this PhD relates strongly to the notion of temporal permeability explained in Chapter 2. The relationship between permeability and convenience is summarised by Higgins and Swartz (2018): "convenience of new urban design rests on permeable land use". The temporal aspect of permeability that was introduced in Chapter 2 focused on the situational opportunities given to pedestrians during their travel (e.g., pedestrian traffic lights that give access when green and limit access when red). Therefore, using temporal permeability here I aim to address the dynamic character of the pedestrian negotiations and of course investigate the pedestrian use of the street rather than the vehicle use.

Faster moving vehicles temporarily occupy the space as they pass through. On the other hand, pedestrians who spend more time in this space are required to follow rules even when the space is underused or vacant in order to avoid conflicts with cars. However, some pedestrians, if they can, try to make use of this underused, over regulated and sometimes vacant spots of the street (i.e., opportunistic pedestrians). Whilst using these spaces, pedestrians are often unprotected, unsafe and demonstrate risk-taking behaviour. Through using temporal permeability, in this intervention, I aim to create a refreshed understanding of space by focusing on the slower actor in space – the pedestrian – and balance the different rhythms of road users. I aim to achieve this by looking at aspects such as travel paths, preference of crossing locations, the temporal distribution of pedestrian usage.

Through this conceptual framework, the intervention that I will be applying in this study can be summarised as *dynamic pedestrianisation of streets based on the temporal patterns of pedestrians*. Pedestrianisation, which was introduced in the Introduction chapter, was situated in this intervention in a temporal and dynamic setting. Whilst pedestrianisation often refers to exclusion of all traffic from a certain area, in my PhD it is conceived as a way to focus on pedestrian movement and arrange vehicle flow responsively, increasing pedestrian convenience and safety. In the example discussed here, the activity sensed is the changing distribution of pedestrians in the selected areas. The response of the intervention is controlling the volume of traffic based on the pedestrian activity.

The intervention is envisioned as mimicking natural vision by perceiving the pedestrian agents in the areas the vehicle is about to enter and arranging the vehicle flow based on them. The system was envisioned as an IoT enabled intelligent sensor that is able to communicate pedestrian position and volume data to the vehicles and vice versa through its interfaces in the street. A general overview of the components of the system are (1) a sensing mechanism that senses pedestrian data, (2) processing the sensed information by comparing the two routes available to the vehicle, (3) selecting a route and (4) informing the vehicle as well as pedestrians. The input of the system is pedestrian position and density data. The output is redirecting the vehicles towards the less pedestrian populated areas. In this section, I will explain how I applied this system into the simulation. Later in the chapter, I will also summarise how it could be applied into a real environment by giving examples, showing how informative output might be provided and other potential dynamic interventions that can be tested.

Two sets of variables are sensed in this intervention: (1) the pedestrian volume and positions and (2) the position of the vehicle. The pedestrian volume and positions are sensed through separating the virtual space in the simulation into modular segments. These segments check how many pedestrians are present within them. These segments are located along the potential routes that the vehicle is going to follow. Each route is aware of the segments of which it is composed, so, when a vehicle is at a decision point such as a junction, the intervention can check the sum of the segments along each route. A decision point is created by selecting a location where the intervention will be activated (Figure 7.1). In this case, these points were always at the junctions of at least two potential routes the vehicle might follow (Figure 7.2).

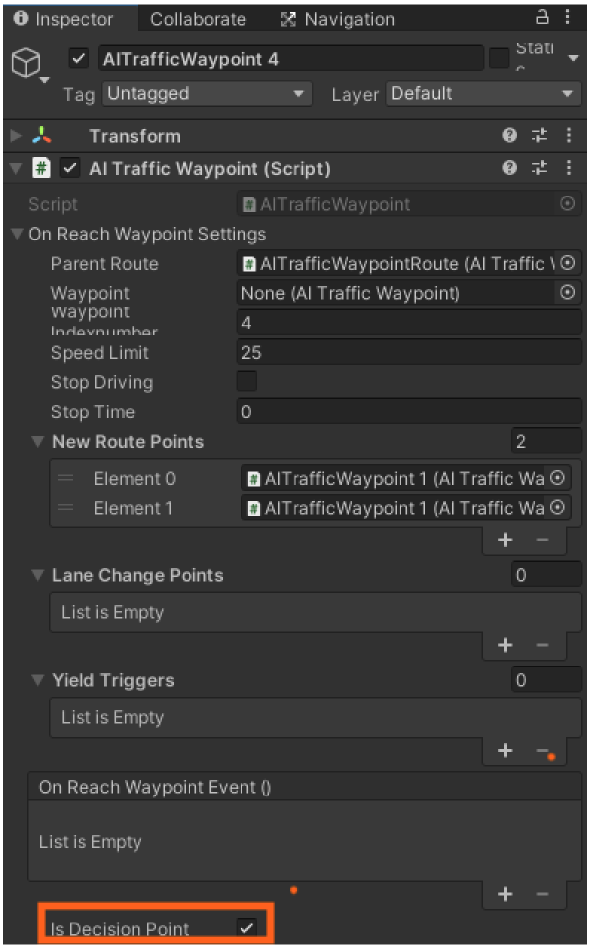


Figure 7.1. Selecting the Waypoint as a decision point indicated with orange square.

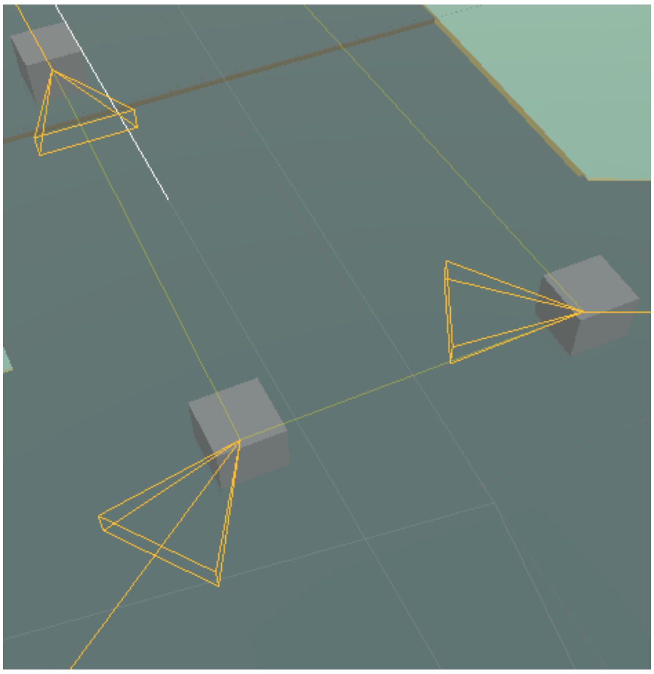


Figure 7.2. A waypoint example that is connected to two potential routes that a vehicle might follow.

When the vehicle is at this decision point, the intervention decides which route the vehicle should follow. This decision is made through comparing the volume of pedestrians on each route, allowing the route which has the lower number of pedestrians and avoiding more densely pedestrian-populated areas. In summary, the input to this decision is (1) segments in each route collect data about pedestrian position and volume, (2) this data is compared at the decision point where the vehicle is positioned, (3) the decision point makes available the route with the least pedestrian population near the highway. Through this process, the intervention regulates and distributes the volumes of the different mobility types based on the situational information made available to it.

The temporal part of the intervention comprises determining when the intervention is activated, when the segments of the pedestrians are compared, and when the intervention diverts vehicles. As already indicated, the intervention is activated when a vehicle is at a decision point, and the activation of the intervention triggers comparing the number of pedestrians in the segments: the temporal aspect of the intervention is therefore controlled through spatial events, while the result is the on/off control of the intervention.

The informative output in the virtual environment is represented through animations and visual interfaces. Animations are set to point out when the intervention is happening by changing the camera angle from a single pedestrian view to a macro view (Figure 7.3) and playing the animation, which shows the route the vehicle will follow. The animation colour and the route changes based on the selected route for the vehicle (e.g., the green transparent volume in Figure 7.5 and purple transparent volume in Figure 7.6 indicates the routes vehicle follow at that instance).

The visual interface can be used to compare different intervention scenarios or different intervention examples. The counters show three types of risk-taking behaviours (including stopping, fleeing and re-pathing) and the number of pedestrian hits. These numbers can be used as a proxy to compare different scenarios in order to have an idea about their potential effects.

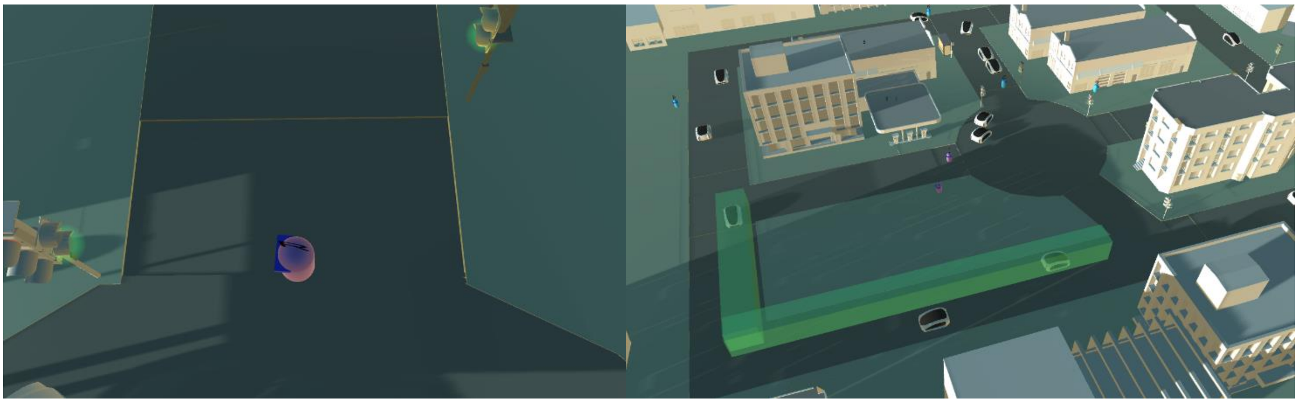


Figure 7.3. The two camera views. Left image showing the single pedestrian view, right image showing the macro view.

Simulation Experiments

In this section, I discuss how designers may use simulations for practising interventions into street mobility. It is important to note that the experiments presented here, my engagement with simulation, and the use of the simulation tool for intervention, co-evolved together. Hence, the reflections and simulation experiments have emerged from implementing the intervention as much as the reflections emerged from experiment; an approach familiar in Research through Design, as discussed in Chapter 4. For example, here the simulation experiments are used as a reflection tool in order to understand and articulate the different uses of a single intervention rather than discussing its outcomes in the potential of direct implementation in the real environment. Therefore, rather than applying interventions as a step-by-step method, the following conceptual experimentation is intended to put flesh on the skeleton described so far.

I began applying this intervention by using one decision point and trialling whether the intervention was working correctly in a test scene (Figure 7.4). In this scene, I have used only stationary pedestrian agents and changed their positions manually, in order to monitor whether the animations and interventions were working correctly. To control the volume of vehicles, the functions included selecting one of the two routes based on the pedestrian volume.

When a vehicle approaches the decision point, the intervention is activated, and the camera view switches to a macro view to notify the observer that a vehicle is approaching the decision point. On the decision point, vehicles can take one of two routes: route A or route B. Therefore, the intervention compares the segments assigned to route A with those assigned to route B. The route with the fewest pedestrians in its segments is then chosen. Once the selection is made, the vehicle proceeds on the selected route.

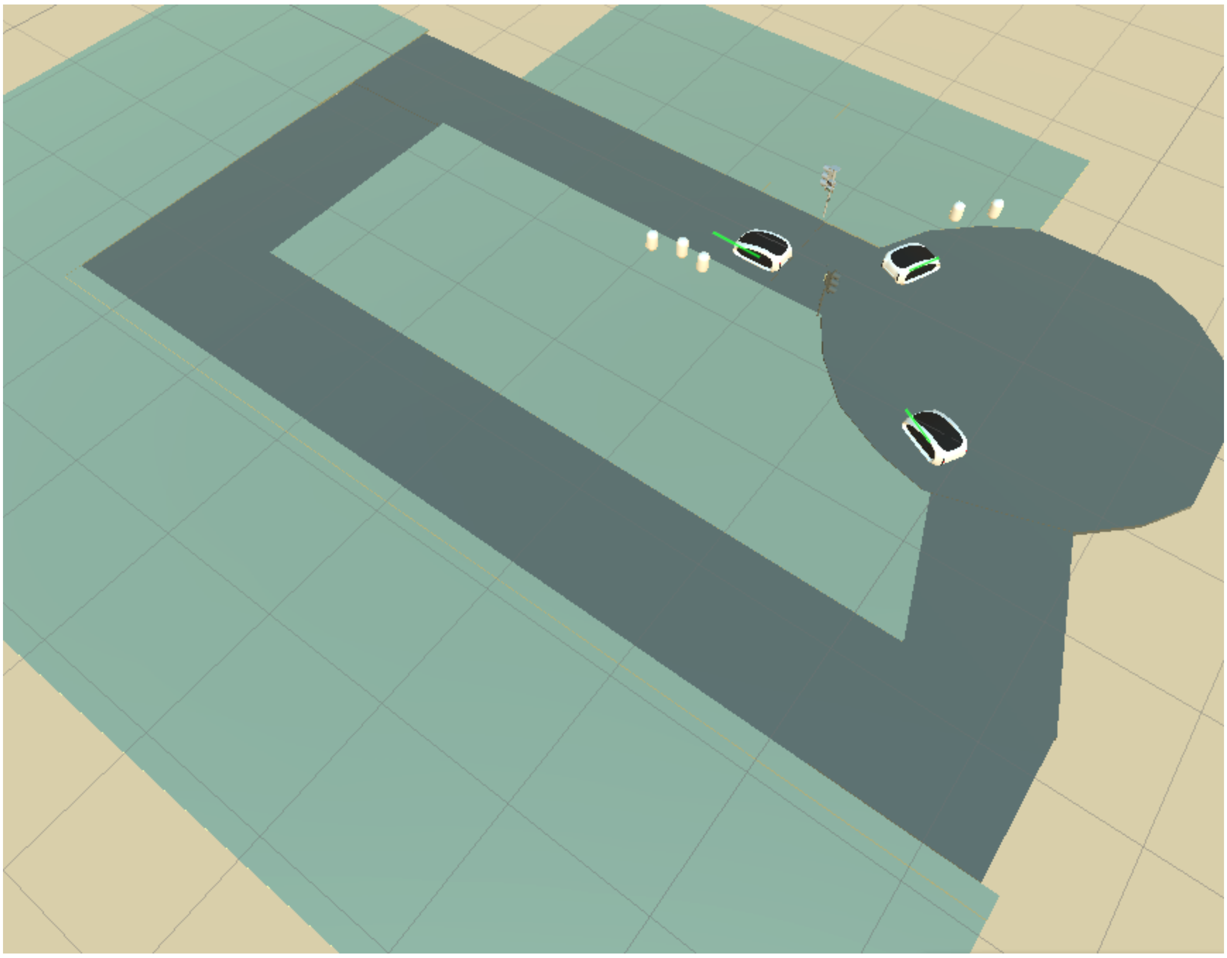


Figure 7.4. The test scene which shows static pedestrian agents as white capsules and three vehicles.

A separate animation plays in each route, as the animation's purpose is also to show which path the vehicle will take. I produced animations in the form of volumes that depict the route the car will take. The example animations can be seen in Figure 7.5 and Figure 7.6.

The term experimentation is used here in a broad sense to describe any form of empirical testing of the intervention as described in the previous section by introducing it in different settings as a virtual prototype. By 'reflection on the intervention' I refer to my review of findings and observations rather than a performance analysis. The qualitative and quantitative outcomes of the experimentation map the consideration points about the intervention. The goal of these consideration points is to guide the development of interventions and report on what is the potential for the dynamic street approach. As McKenney and Reeves (2014) state, the reflection process attempts to offer a deeper knowledge of the intervention, the appropriateness of its purposes, how it appears when performed, and the consequences it yields under certain conditions; this serves as the foundation for recommendations regarding intervention refinement.

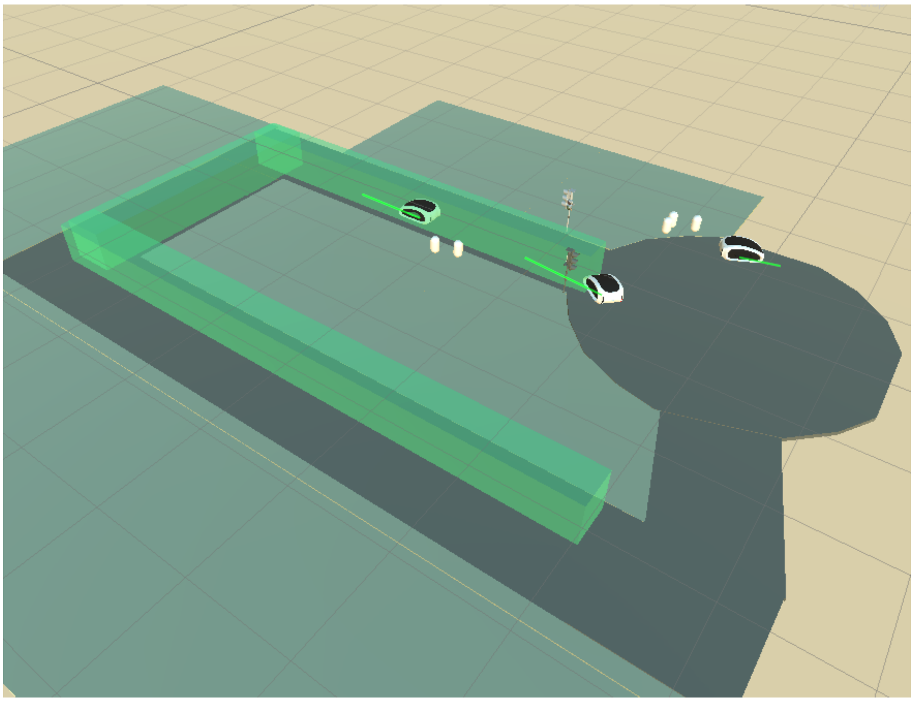


Figure 7.5. Animation one which indicates the route that is going to be followed after the decision point where the vehicle is entering to the route at the beginning of green volume.

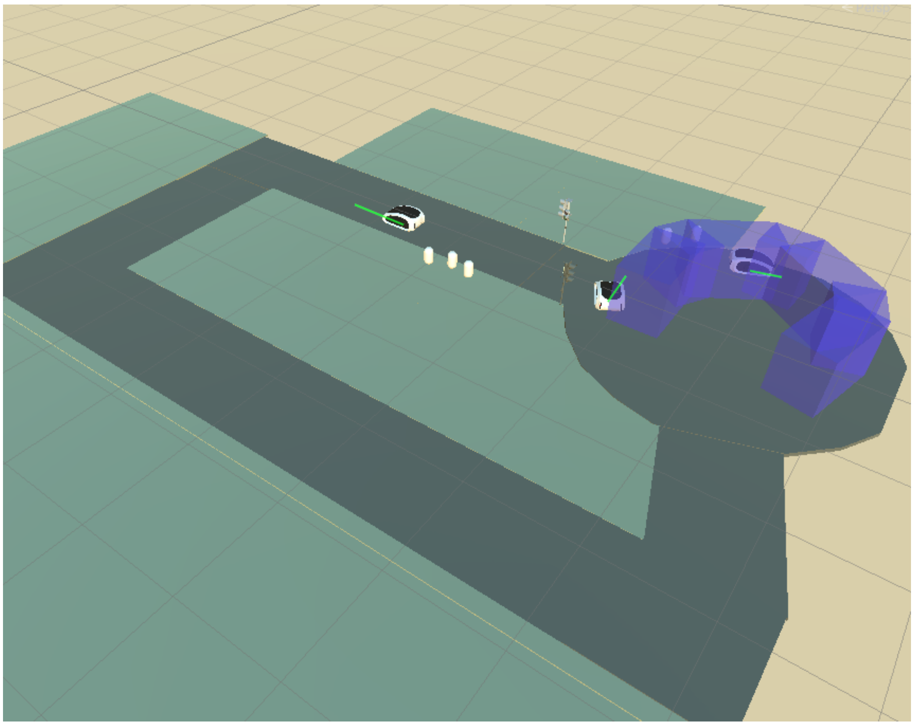


Figure 7.6. Animation two which indicates the route that is going to be followed after the decision point where the vehicle is entering to the route at the beginning of blue volume.

With this intention, I decided to explore the intervention through three aspects: temporal, spatiotemporal and pedestrian dynamics. These three aspects are selected in order to consider potential refinements of the intervention on three core points this research is based on: temporality, spatial circumstances and use of various pedestrian characteristics. The testing of various pedestrian dynamics is embedded within the temporal and spatial experimentation. This means that the pedestrian characteristics that were established were adjusted in a controlled manner in both aspects in order to better grasp the outcomes of the intervention.

Temporal Experimentation:

At first, my interest in the intervention was seeing how the temporal aspects (such as assigning waiting time at the decision point to the vehicles or having a more active intervention which doesn't have waiting time) were changing its effect. Therefore, I have applied the intervention in two different decision points: one with a traffic light and one without (Figure 7.7). The traffic light causes a delay to the intervening process of the intervention, whilst the decision point which does not have a traffic light is more instantaneous. I was interested to find out how this temporal difference (waiting then intervening vs. immediate intervening) might affect vehicles and pedestrians. To see the effects on vehicles, I observed the occurrence of traffic, whilst to see the effects on pedestrians I observed the visual interface (which includes the numbers of risk-taking behaviours and the number of pedestrian hits).

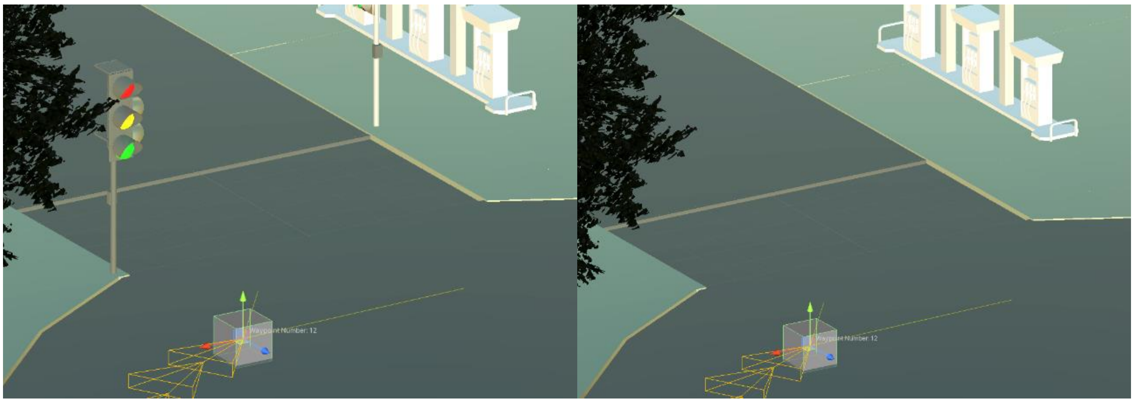


Figure 7.7. The intervention applied to the decision point where there is a traffic light vs. the intervention applied to decision point without a traffic light.

The intervention is applied to a single decision point. In order to create a dynamic pedestrian circulation, I have distributed pedestrian starting and destination points around the decision point. The destination points are shown in Figure 7.8. The pedestrian groups arranged in the intervention had mixed characteristics which include equal numbers from each group, namely 2 rule-following pedestrians, 2 opportunistic pedestrians, and 2 eager pedestrians.

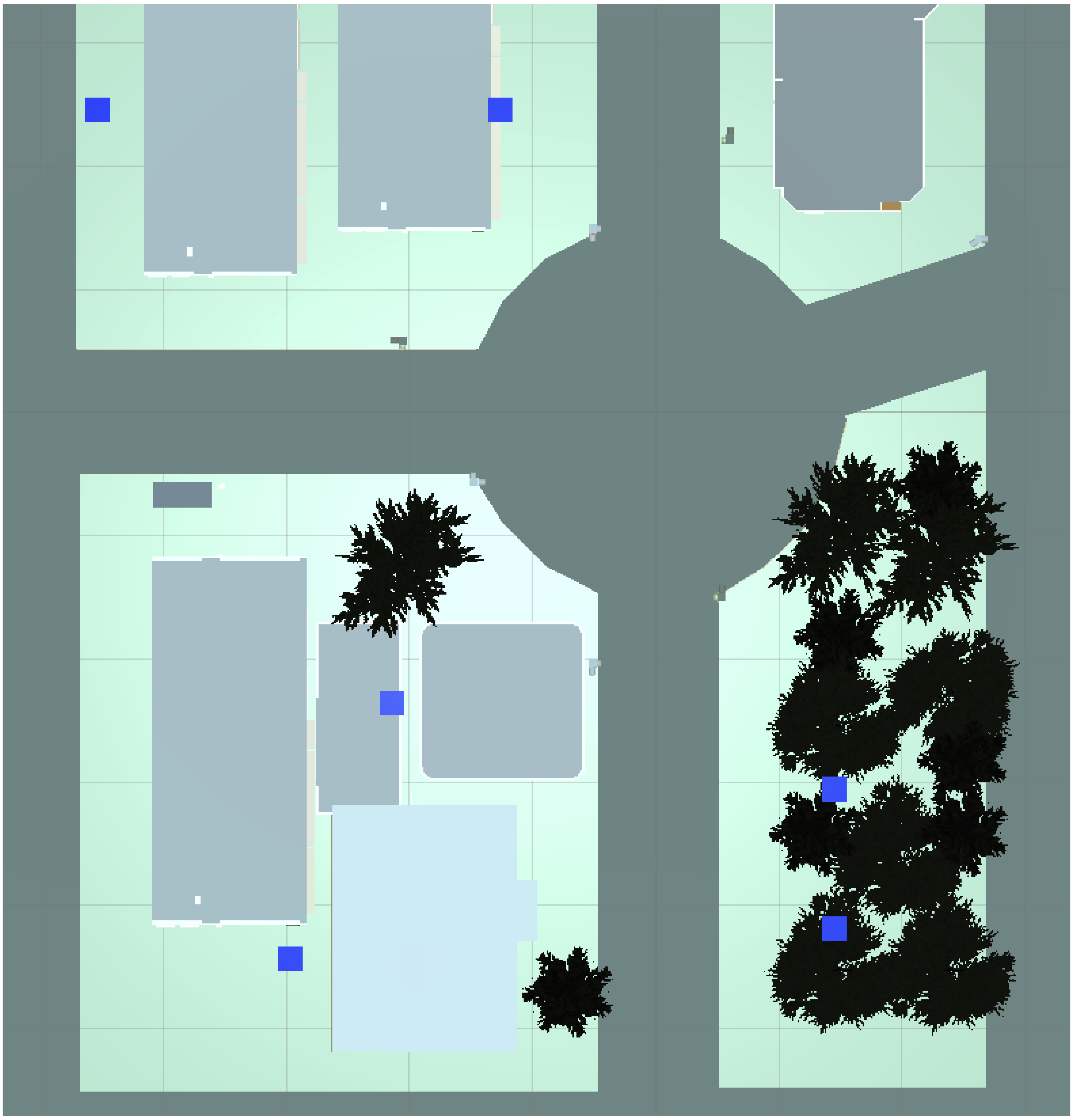


Figure 7.8. Destination points of the Pedestrian Agents. The blue squares represent the destination points.

The observation of the simulation experiments on the temporal dimension had a number of outcomes. When the traffic light is coupled with the intervention, the temporal scheduling of the intervention is distributed more evenly, therefore, the intervention is triggered less often, enabling multiple vehicles once triggered. On the other hand, when the intervention is used without the traffic light, intervention gets triggered more often causing an increased number of instances following one another.

When the intervention is linked with a traffic light, one of the consequences that must be addressed is that the timings of the intervention should be in sync with the traffic light. When one route is open to vehicles, the pedestrian signal should be red on that route whilst the traffic light is green, and vice versa for the other route. Therefore, one of the outcomes of implementing the intervention could be the reciprocal scheduling of the intervention with the traffic light.

Another interesting observation of the temporal experimentation is that when the intervention is not coupled with the traffic light, a slight increase in the vehicle traffic (the throughput of vehicles per unit time) is observed. This is perhaps related to not dividing up the vehicle volume through traffic light interruptions and therefore resulting at the end with an increased traffic volume.

I discovered that the quantitative data about risk-taking behaviour occurrence and numbers of pedestrian hits was not very consistent through the experimentation. Therefore, the effect of using traffic lights or not using traffic lights with the intervention should be further investigated in detail to better comprehend its effects. The initial experimentation shows that the numbers of hits and risk-taking behaviours are slightly reduced when the intervention is used without traffic lights. This may be because the intervention is more responsive and dependent on pedestrians in a more timely manner when it is not combined with the periodicity of the traffic light.

Spatiotemporal Experimentation:

Using only one decision point did not create a fully pedestrianised street (where the spaces for pedestrians and vehicles are completely separated) but aimed to create a vehicle flow control on the street. In order to have a temporarily pedestrianised street, both the entering and exiting points of the street would need to be making the same decisions. Therefore, to understand this situation, another scene was created. This focused on exploring the spatial outcomes of two different intervention points at each end of the street. The exploration aimed to observe temporal changes on spatial characteristics.

The decision of choosing one street or another occurred at different times for the vehicles that are at each end of the street (Figure 7. 9). This resulted in either fully pedestrianised streets or reduced vehicle flow in the street. Most often, the area of focus had a reduced vehicle density. In addition, dynamic full-pedestrianisation is observed occasionally. This signals that if the intervention's aim is full-pedestrianisation of the selected area at certain times of the day, the intervention points should be synchronised or have a delay. This should be tested as a next step at the virtual environment, by adjusting the logic of the intervention. This temporal adjustment could be made by adding traffic lights to both intersection points to create delays and allow temporal full pedestrianisation on the street through stretching the intervention's timeline. Another way to adjust the logic could be through syncing the interventions with each other.

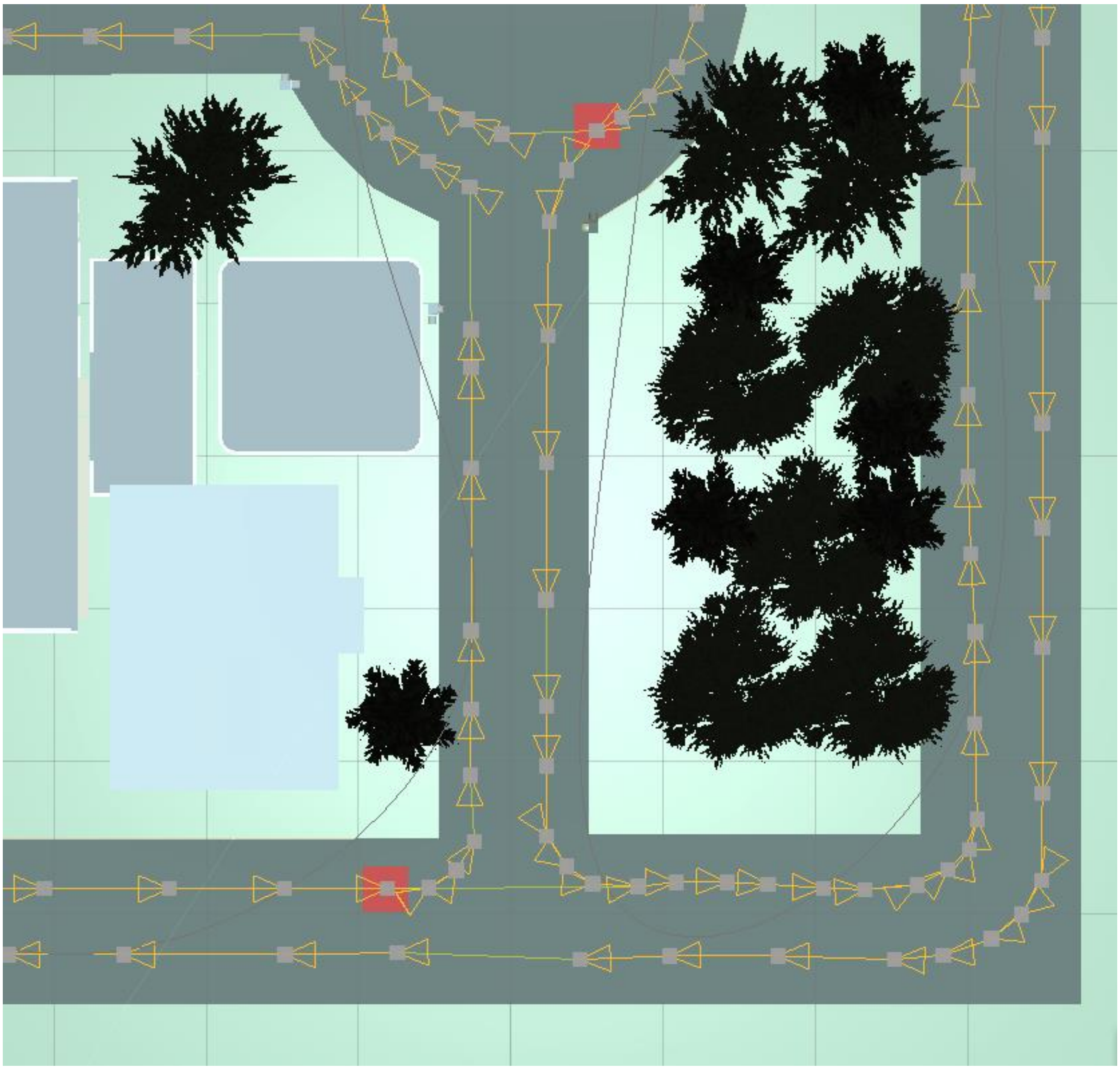


Figure 7.9. The locations of the Intervention. Showing the decision points that are selected at each end of the street. The red dots represent the decision points.

Guidelines for the Intervention:

The first step during identification of unexpected or unwanted outcomes of the intervention is to clearly represent the problem, which requires understanding the internal processes and their representation in the simulation. Through this understanding, it is possible to restructure aspects of the system so that the model can lead in a different direction. When the model is repetitive and showing strong indications (such as giving too often certain results), it might mean that the interacting parts of the intervention is leading the system into trouble. Conducting investigation in order to understand the underlying mechanism that generates these problems is approached in this PhD by testing in a simplified environment, repetitive observation of the system and conducting experiments with changed values or parameters.

Through these experiments, a number of weaknesses of the intervention have been found out: (1) assigning segments to check the pedestrian positions and movements for the intervention, (2) traffic occurrences where vehicles become stuck in the traffic system. These are discussed in the next paragraphs.

In the first part of the testing, one aspect of the intervention that was spotted was the volume of segments assigned to check pedestrians. The volume of segments should be approximately similar in between the routes otherwise, the route choice becomes almost static as the decision point always sends the vehicles to the route which has the lower volume.

Another point which was present in both temporal and spatial experimentation was the occurrence of excess traffic because of the lack of route choice. To avoid complications in the traffic management in the simulation, the route planning of the vehicles was implemented as a simple system with the least amount of connection points in order to avoid crashes between vehicles. However, when the intervention was implemented, this mindset caused more traffic as vehicles were getting in a vicious circle (Figure 7.10). This can be arranged by better planning of the traffic flow and adding more connection points where vehicles can change lanes and routes.

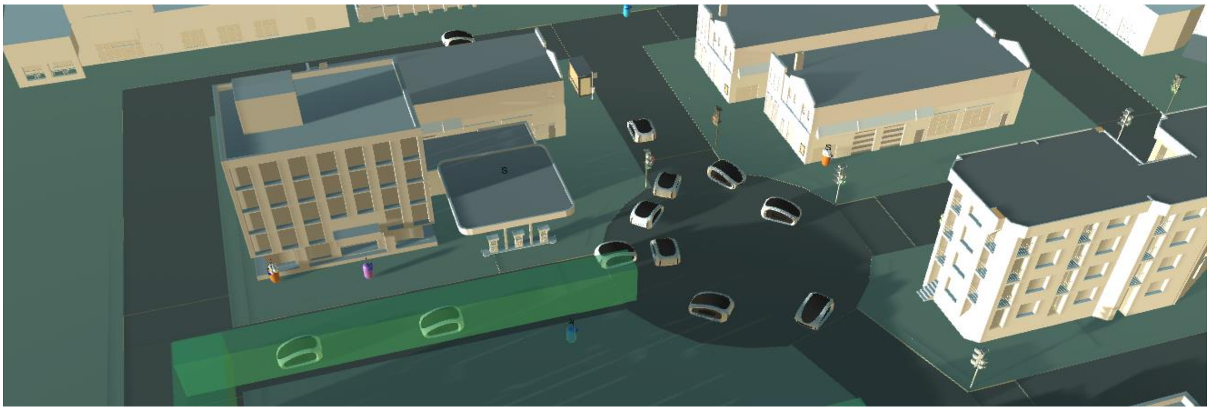


Figure 7.10. Vehicles in a Loop as a result of lack of connection.

Potential Steps Towards the Real World Application and Future Possibilities

When translating the virtual version of the intervention into a real-world proof-of-concept, one aspect to consider is translating the requirements for the intervention from the virtual to the real world. In the requirements of intervention section, I have discussed four aspects to keep in mind:

- Sensor or sensing mechanism
- Response and the functions to show that response
- Temporal aspects such as when or how it is triggered
- Informative output such as how and to whom it is communicated

In this section, I will discuss these aspects respectively to facilitate the translation from virtual requirements to real-world applications by considering a number of concepts and examples that can be used in this specific intervention.

A factor that must be considered carefully is the sensors or sensing systems. There are number of technologies available which I outlined in the Introduction Chapter, including but not limited to sensors used on autonomous vehicles such as Lidar or real-time image processing through computer vision, IoT (internet of things) applications for smart cities, load cells which are used to translate the weight change into an electronic signal, GPS signals, or surveillance cameras.

When selecting a sensing mechanism, it is necessary to define what type of data will be required. In this intervention, for example, the sensing mechanism had two properties to sense, when a vehicle is at a junction of two routes, and the volume of pedestrians in each route when the vehicles are at the junction (decision point). The presence of a vehicle at the intersection is required to initiate the intervention and activate the pedestrian detecting mechanism.

In pedestrian sensing, one way to detect the presence of pedestrians and their direction of travel could be through using multiple PIR sensors. These sensors were previously used for pedestrian position and direction by Akhter et al. (2019), where they have also been supplemented with ambient monitoring sensors that sense temperature, humidity, pressure, CO2 and other compounds present in the air. This ambient monitoring aspect could also be used to create other dynamic interventions (e.g., seasonal streets). I singled out this example as it does not rely on privacy-invading technologies such as mobile phone tracking, surveillance or face recognition.

For sensing vehicles, there are numerous applications of vehicle-to-infrastructure communication that focus on creating a communication system for vehicular networks. The majority of the examples in this category rely on wireless communication (e.g. Dey et al., 2016; Meneguette et al., 2018; Sherazi et al., 2019). These systems make use of modern technologies that are embedded in vehicles such as sensors for vehicle's speed, position, heading and acceleration (Vieira et al., 2017) and could communicate these data to the infrastructure. Further, these communication systems (such as connected vehicles) are developed in order to use these technologies to improve safety and address congestion. Other forms of data transmission between vehicles and the infrastructure can include using cellular data (Busari et al., 2019) and GPS (Dey et al., 2016).

The nature of the response of the intervention to the sensor data can be the same as in the virtual environment, namely deciding between the routes made available to the vehicle according to the pedestrian density. The communication of this information with pedestrians and vehicles would require research on the effective ways to communicate with these groups on the street level. As described through the taxonomic review of practical pedestrian related interventions in Chapter 2, most often dynamic interventions are communicated through an interface on the ground (e.g. the smart crossing concept by Railston and Gamlen (2020), smart surface by Umbrellium (2017), smart tactile pavement by Büro North, (2016)). This could be one way to approach communicating with pedestrians. Furthermore, it could be enhanced with certain characteristics embedded in the street surface level such as subtle changes in patterns through physically reconfigurable geometries (e.g. Everitt, 2020) to inform the pedestrians who are visually impaired. This would clearly require extensive testing.

Other potential points to consider in this intervention is how this could affect the traffic, drivers or passengers who need access to specific locations within the temporally pedestrianised street. One approach to this could be to link this intervention with route planning algorithms for drivers. This could get an estimate about the density in the areas between different times of the day and organise the route planning of the vehicle accordingly. Another approach could be adoption of shared vehicles. This could potentially reduce the car parking need and pedestrianised areas could serve the passengers which can increase the number of pedestrians in the area. For these implementations, perhaps the intervention could be enhanced by adding vehicle characteristics into the simulation such as creating shared vehicles where partially pedestrianised areas are used as drop-off points. By using already existing road space, the shared vehicles would not reduce the existing pedestrian space and the speed of vehicles in the partially pedestrianised area would reduce.

Discussion of the Intervention Experimentation

This study has illustrated the introduction and implementation of an example intervention. The chapter has particularised the broader discourse in this PhD that seeks to better understand what constitutes a dynamic pedestrian-centric intervention. In addition, the chapter explains how one can use the simulation tool in order to improve and comprehend a planned intervention. By demonstrating temporal and spatial experimentations, I aimed to display the simulation tools' potential to conduct experiments that would be challenging or impossible to perform using the traditional approaches, using simulation's ability to represent a large number of variable elements. Based on the points of interest and settings decided by a researcher, the use of other factors, levels, or even scales would be an intriguing path to explore for future research. This chapter has shown how practice-based design can be integrated in a simulation tool and how the outcome indicates a path for progress in the intervention. While the chapter indicates how an intervention can be modelled and implemented, it also offers insights on the inner workings and functionality of the intervention. Referring to Gaver (2012), this dyadic interaction entails elaborating on the impact of reflections through improving the intervention. This aids in learning from the application of intervention into the virtual environment via experiments that supply both visual and procedural evidence of the impacts and outcomes.

On the Notion of Dynamic Pedestrian-Centric Intervention

The dynamic approach described here is intended to challenge the current conceptualisation of the street by approaching it with a pedestrian-centric mindset. The focus of observing and understanding the environment and pedestrians has been combined with a safe space for exploration in order to extend and discuss the potential for dynamic interventions.

The use of dynamic intervention serves to understand the pedestrian positions and movement in order to arrange the density of the vehicle movement accordingly, and sometimes even causing full pedestrianisation of the route. One question to consider is how these kinds of interventions may lead to further changes happening in the street, whether the presence of more pedestrians would attract others or whether people's preferences would change according to the congestion and pedestrian densities. Therefore, this study opens further discussion rather than simply answering a question.

Experimentation serves to initiate activities to imagine alternatives of pedestrian mobility and their interactions with other modes of transportation. Therefore, implementing the alternatives in a virtual environment to learn from them shapes the core of this study. Through this process, experiments provide both visual evidence and outcomes to improve the intervention that is thought and implemented.

Balancing the dynamic approach (which can be linked to obtaining a 'smart' system) and people's interests within the environment can be accomplished by enhancing the intervention's quality of adapting to pedestrian needs. This offers opportunities for people's participation in the urban space by acting and involving rather than following the guidelines decided for them. These pedestrian needs can be expanded with future research by incorporating information from other studies about where people like to spend their time, why people pass along certain streets rather than others, and where they enjoy walking in order to improve their routes accordingly (e.g. Adkins et al., 2012). In the long term, these approaches can empower the pedestrian position in the street by valuing and considering the space they take.

This dynamic intervention aims to create an opportunity to imagine spaces differently and offers an opportunity to intervene in the space based on the present conditions. Therefore, future research could explore how to construct the temporary use of the street by offering opportunities based on the use and rhythm of the street such as markets, playgrounds, installations, activity spaces and other temporary public engagements. In this context, it would be particularly valuable to take people's and public opinions to connect the temporary use of space with their use and vision.

Chapter 8 Discussion and Conclusions

This PhD addresses the question of 'how to design a pedestrian centric street system that dynamically manages street mobility?' by creating a simulation environment based on a qualitative observational study and showing how to experiment to design dynamic interventions. This approach answers the question partially by providing the necessary tools to design a pedestrian-centric street system and demonstrating a preliminary example of a dynamic management of street mobility. However, to create a pedestrian-centric street system, more research is needed in which various dynamic interventions are experimented with in simulation and tested with participants. I believe this PhD opens a discussion by providing a platform and showing a process to work with in order to create this system. In this chapter, after discussing the overall processes and approaches adopted in this research, I will address the limitations, future work, and research contributions.

Designing a Reflective Tool for Designers

The pedestrian simulation presented in this PhD plays two roles: (1) representation of data derived from rich qualitative observations and (2) a reflective tool to allow exploration of new design ideas. These two roles address the gap between the user research and design practice mentioned by Wixon (2003) and that has been addressed by others through scenario-based design, participatory design, empathy tools and other methods (discussed in the Theoretical Framework, chapter 3). A simulation or a game engine, as previously mentioned by Chukhray et al. (2020), can provide a facilitation of information on the interaction and behaviour of individuals demonstrated in a specific environment in order to improve the creative potential of a project. This process, as Dorst and Cross (2001) states, implies an ongoing iteration through analysis, synthesis, evaluation and construction. The relationship between these stages constructs an information flow (feedback loops) where the problem is clarified and framed through acting and reflection. As explained in *Chapter 7 Designing an Intervention*, the feedback loops created by acting and reflecting while using the simulation assisted in moving the design concept of dynamic pedestrian-centric intervention from the realms of the speculative and possible to the realm of the feasible. This aimed to benefit designers, like myself, by allowing them to see rapid feedback on the proposed ideas streamlining the development and deployment of interventions.

One of the functions of simulation was to guide the reconstruction of collected qualitative data. The systematic framework of agent-based modelling included three phenomena: (1) agents, (2) interactions and (3) environment. These phenomena were identified first during the observational analysis phase then in the modelling process. This identification followed defining the characteristics of agents (e.g., pedestrians who follow the pedestrian lights) in order to define their behavioural modules (e.g., perceiving the traffic light), agent's relationship with spatial measures through preliminary route planning (e.g., crossing through the road or through the pedestrian crossing), interactions between these modules (e.g., perceiving a vehicle and categorising that vehicle as dangerous) in order to define interactions between agents (e.g., waiting vehicle to cross) and spatial measures (e.g., implementation of traffic lights, kerb, pavements). This definition process was not straightforward. During the first implementation of the defined behaviours, certain aspects related to the agents were not prioritised. However, during the development of the simulation, they were proved to be important. An example of this aspect is the separation of strategies between short-term and long-term decisions about crossing. As a result, while the video analysis was initially intended to form the simulation, in these cases, the simulation assisted in furthering the video analysis.

Through this iterative process between the two studies, this thesis demonstrates that there is room for improvement in conventional applications of pedestrian agent-based modelling simulation. Further, the combination of methods benefits video observation study as well as the modelling process, emphasising the importance of *making* as part of the process of problem-framing and definition of the research question. Schön (1983) and Dorst and Cross (2001) suggest this 'problem setting' or 'problem framing' helps to increase the performance of design practice through generating insights in the process.

The second role of pedestrian simulation described in this PhD is its usage as a reflective tool for research through design. This reflective use draws a more similar use of agent-based modelling with López Baeza et al. (2021) where the simulation models inform the decision-making process of urban and landscape planners by demonstrating the pedestrian activity levels, flow and distribution. Similarly, my PhD presents a tool to transform design ideas from basic principles into a proof of concept. The use of agent-based modelling simulation as a research through design tool is demonstrated in the intervention study as a way to overcome the separation between research and design.

Agent-based modelling and video observation techniques are previously adopted by other disciplines from social sciences, but here, the choice of engine (Unity3D) as a simulation model was a critical point in the research. This choice has been made for several reasons (see Chapter 6, Choice of Engine Section), however, one important aspect of it is that its accessibility and wide adoption in the design community. Creating a virtual space aimed to enable designers and other researchers to explore measures that would not be possible to explore in the real pedestrian environment. This feature of simulation contributes to the objective of "challenging existing constraints" (Giacomin, 2014) – going beyond minor modifications of existing concepts – mentioned in the human-centred design section (in Chapter 3) by understanding and exploring the nature of street behaviours.

Furthermore, simulation provides a systematic approach to folding critical reflection into the process of designing interventions. Through providing feedback, simulation helps the designer to reflect. This reflection allows identifying blind spots and improving the idea's practical aspects or opening new design spaces. By enabling questions such as what is occurring when changing certain parameters, what this is triggered by, why this is the result, the simulation creates a more responsive design process where potential consequences of the intervention are signalled through its outputs.

Reflecting on Pedestrian-Centric Street Mobility

The pedestrian-centric approach towards urban spaces is studied widely as identified in the Introduction and in the Theoretical Framework chapters. My research directly addresses this topic but takes a different approach from previous studies through focusing on pedestrian crossing dynamics, interactions and behaviours in order to impact on safety and convenience of pedestrians. Through the research, a particular focus is given to understanding and simulating the pedestrian's situational context, how pedestrians use these situations and how these uses differ amongst the pedestrians. This approach makes use of Gibson's (1966) theory of affordances (see Theoretical Framework Chapter, The Theory of Affordances section) as it also considers objective possibilities of how a situation (in Gibson's case, environment or object) might be viewed and acted upon.

This flexibility – viewing the pedestrians as individuals who can use different situations in various ways and can behave differently from each other – is implemented in the simulation. This approach differentiates the pedestrian simulation in this PhD from the traffic-centred simulations that simply include pedestrians. As mentioned in the Agent-Based Modelling chapter, the pedestrian agent-based models often focused on single aspect of pedestrian crossing behaviour (e.g. Sargoni and Manley, 2020; Xi and Son, 2012; Yang et al., 2017; Zhuang and Wu, 2013) and therefore had a partial representation of pedestrian behaviours. In this PhD, by aiming to expand the representation of different pedestrian types, I built a pedestrian-centric simulation in which diverse pedestrian behaviours and possibilities of action during the negotiations with vehicles are represented. As a result, this research has generated an example and a context missing from evaluating pedestrian and vehicle populated environments, by using a dynamic approach.

The pedestrian-centric approach when applied to design interventions in the streetscape opens a new discussion on how to approach the subject of designing around activities of pedestrians. It builds on top of the previous research on pedestrianisation (e.g. Soni and Soni, 2016), walking (Southworth, 2005), desire lines (Smith and Walters, 2018) and strategies such as traffic calming (e.g. Pérez-Acebo et al., 2020) by framing them through the technological tools. The intervention represented here is defined as dynamic, this meant including features such as sensing, responding, communicating and considering temporality. Through these features, my research connected the realities of pedestrian behaviours with the future of concepts such as smart cities, aming to ensure that pedestrians are not an afterthought to such visions but a central concern.

Pedestrian empowerment in this context is addressed by seeking for pedestrians both convenience and safety in the street mobility space. In the words of Furman (2017): "any form of empowerment that builds the levels of comfort and safety creates opportunities for other affordances on the street that were previously unthought of, especially if a street was felt to be alienating and dangerous". The potential implications and further research opportunities presented at the end of the third study chapter reflects on how potentially a dynamic approach towards the street can mitigate certain challenges and offer potential ways to approach those issues.

Designing for the Dynamic (Responsive/Adaptive) Street

The dynamic approach employed in this PhD considers primarily pedestrians. It aims to adapt the street mobility to them through designing interventions. The example intervention in the third study illustrate this principle by changing vehicle density and flow based on the pedestrian density. Through this example, I aimed to show one way of using responsive, adaptative and dynamic approach in the context of pedestrian centric street mobility.

Reflecting on this intervention, the dynamic approach where the street adapts to pedestrians can have certain implications on other aspects of the street as well (as discussed at Chapter 7). These implications can include applications of more contextual and inclusive urban form through opening and exploring other options, moving away from standard solutions. This is enabled by perceiving the environment outside of top-down constructed norms and looking at local patterns generated by pedestrians. It reflects Gibson's mission to "learn to see what things really are…" (1979, p.130). The dynamic intervention, therefore, aimed to understand how things work and happen, and exemplified how we can design based on these processes. This ultimately brings the concept of adaptation where the street adapts to pedestrian processes and changes according to them.

Adaptation in this research is seen as a process rather than a one-time solution. The methods and techniques I have employed are chosen to contribute to this process. This 'adaptation' perspective itself became valuable to show why design research does not just provide solutions but also should question and reframe the problem. Through this lens, this investigation brought a different approach to intervening the street which can help to understand and change the relationship between pedestrians, vehicles and infrastructure.

Bridging Between Diverse Fields

It can be challenging to bridge between qualitative study such as video observations and computational tools. There are different understandings about what constitutes a valuable research contribution, how data should be presented, what constitutes a simulation tool and what kind of evaluation is appropriate. Combining these research elements with the design field was another node of this research. However, there are certain conceptual connections in the literature that helped to connect these nodes such as using affordances for agent-based modelling (Turner and Penn, 2002) and using affordances in design (Krippendorff, 2005). Yang and Gilbert's (2008) work on bridging qualitative research and agent-based modelling was another useful example supporting the methodological process in this PhD.

A significant challenge has been the identification of necessary qualitative information and its translation into the simulation. One of the questions I received during an artificial life and simulation conference concerned the use of qualitative research as a data collection method: I was asked whether it was possible to change this to automated data collection using techniques such as machine learning. As I discuss in the Methodology chapter, one of the reasons to use video observation was to interrogate the relationship between pedestrian actions and surroundings. I believe my results show that the method I developed reveals more than could have been discovered using automated techniques. They allowed simulation to have an innovative level of variety because the qualitative data represented a level of individual differences and subtleties amongst pedestrians.

Visualisation as a Data Extraction Technique from Video Observations:

The video recordings by themselves constituted an extensive source of information. Making sense of this information and identifying the useful parts of it was first achieved by transcription and using interaction analysis. Capturing the video data through transcriptions was useful, however, it was not sufficient to identify the relationships within this information. For that reason, I needed to create a visual framework to show the relationships between the situational, environmental, temporal and behavioural information. This was useful later on for creating the agent's behavioural sequence for simulation.

Additionally, further data extraction occurred while creating the process of simulating pedestrian agents. One example of this was creating long distance risk perception and short distance risk perception for pedestrians. Whilst long distance perception involved making strategic decisions about avoiding vehicles prior crossing, the short distance perception involved activities to avoid vehicles during crossing.

Agent-Based Modelling as an Analytical Tool

After visualisations of transcripts, the agent-based modelling served as an analytical tool to translate observational data into the simulation. It was particularly insightful to address observational data through simulation as it extended the representation of pedestrians. Throughout the simulation, the visual interface of the simulation prompt reflections and stimulated new questions about the processes occurring in the simulation.

The analysis of the intervention through the simulation occurred in two ways. One was through observing the effects of interventions visually, other was through the informative interface. This analysis helped to capture the initial problems about the intervention and gave insights about further improving the intervention. Based on the problems and insights, several suggestions are made to improve the intervention and for further research.

Limitations and Future Work

While qualitative observations and computational techniques were used to form this research and had many benefits by allowing to explore and reconstruct pedestrian behaviours, they also had certain limitations. In this section, I will highlight these limitations and suggest how they might be addressed.

One limitation of using only video observation was confirmation bias (Marsh and Hanlon, 2007). Through the study, I have studied the video recordings by organising the events, people, places and named the situations occurring in the environment. Including user reflections on the observed actions, whilst perhaps improving the simulation can also bring more insights on the perception and thinking of pedestrians into the research and could contribute to the development of artificial agents by improving the subtlety of their behaviours. Collecting participants' observations and reflections on the simulation of pedestrian behaviours might indicate potential improvements in this part of the research as well. This could improve the reliability of simulation which would in turn contribute to framing the interventions.

While the behaviours analysed and implemented in the simulation were developed based on the real world behaviours, they do not represent the total variety of pedestrian behaviours. Further work with a more diverse and extensive dataset would widen the representation. Larger samples can especially be useful to create datasets for testing different types of pedestrian characteristics.

Although automation and machine learning and artificial intelligence has recently gained a lot of attention in the domain of analysing human expressions and behaviours, it has not been the focus here; this PhD, in fact, has stressed the importance of using qualitative analysis whilst generating a computational simulation. The aim in this approach was to move away from the oversimplification associated with some digital models and show instead the variety of interactions and behaviours. This approach puts this research in the intersection between the computational models of urban transportation and 'the humanity and richness of living city' celebrated by Alexander (1965). By using qualitative approaches, I aimed to balance these neglected parts of the real world in the computational representation.

One of the criticisms levelled towards computational methods has been their reductive approach, as well as their lack of public engagement and involvement (Mattern, 2021). I have explained above how I attempted to capture more of the richness of human behaviour than is normal in pedestrian simulation. But in addition, my objectives in making the simulation are not to narrow down a range of possible design 'solutions' towards the end of the design process. In this research, the computational approach is used to support the exploratory process at an earlier stage. This meant using the simulation to bring the ideas further and reflect on them before implementation. Through this process, the intervention idea is framed, and its potential and limitations are outlined with suggestions.

Some of the pedestrian behaviours that are more in the strategic and macro level such as pedestrian route choice were not the topic of this PhD and therefore are not explored. However, it is possible to create more complex behaviours by merging this pedestrian simulation with a more elaborated pedestrian route choice model.

There is a growing interest in pedestrian behaviours in the automotive industry with the arrival of autonomous vehicles. I would argue that the studies developed, and the overall outlook of this PhD investigation, are future-focused not just for pedestrians but for many other aspects of the future of mobility.

In the future, it would be interesting to investigate many other dynamic design interventions using versions of the tool I have created. The way the tool is used might also be developed through virtual reality versions, allowing interventions and interactions with simulated agents to be evaluated through participant interaction. An example of such implementation was made by Yang et al. (2021) by combining agent-based simulation, serious gaming and co-design methods to get insights about various urban design alternatives related to public spaces and buildings.

This research offers a unique approach to achieving systemic change in the street through pedestrian-centric strategy in the design field. This can allow us to have a grounded discussion based on showing and communicating the premise of applications. With this objective, simulations can be a useful way of demonstrating these applications.

This research, by using a dynamic approach to studying streets, offers a platform and tools for other designers who are interested in working for pedestrian-centric approaches towards street mobility and experimenting to build novel interventions. This can broaden the field of pedestrian-centric design beyond physical implementations to more technological ones on the street, involving pedestrian aspects in the design process. This provides a testing ground for unique and innovative ideas that are excluded from mainstream ways of thinking and cannot be evaluated in the real world.

Research Contributions

This PhD research focuses on designing a dynamic intervention for the street environment by understanding the behaviours of pedestrians. In the following section, I will provide a series of statements on how the PhD contributes to a significantly under-explored area at the intersection of pedestrians, mobility and environment. The research resides within the wider subjects of human-centred design, intelligent mobility, interactive systems and system-oriented design. *Human-centred design* is contextualised in this setting through pedestrian-centric design, which aims to comprehend pedestrian perspectives by investigating their relationships and behaviours within the environmental context in order to design interventions. My interpretation of *intelligent mobility* has meant putting the human experience at the centre of street mobility by employing technology to address long-standing challenges presented by car-centric thinking. The field of *interactive system design* was addressed through a pedestrian-oriented field study that focused on interactions with dynamic environments through a cyclical process between video and simulation study. This study was then translated in the last study chapter into interactive system design by exploring the systemic effects on pedestrians and vehicles. *System oriented design* was particularly useful to understand how casual relationships and feedback work in pedestrian practices as well as in the context of creating simulations from qualitative observational data.

The research also borrowed concepts from cybernetics, complex systems, agent-based modelling and video analysis. *Cybernetics* provided a framework for considering and developing the relationships between the qualitative observational study, pedestrian simulation study and interventions. Transportation and street mobility have been considered in this research as *complex* because of their often intractable, non-linear, interconnected relationships. Therefore, complex systems are used as a way to describe the systemic characterisation of the relationships between interconnected and functional varieties. To analyse these functional varieties, *agent-based modelling* was employed. *Video analysis* enabled me to analyse the environmental context the pedestrians are in and identify how the environment (infrastructure, layout, interaction with vehicles) is used by them.

Practice Related Research Contributions

This PhD presents a novel way of categorising pedestrian-related street interventions, investigating and representing pedestrian behaviours, simulating pedestrian interaction using agent-based modelling, and using the model developed as a design tool*. Categorising pedestrian-*

related street interventions resulted in a taxonomic map that expands on the literature review and summarises the spatiotemporal relationship of recent intervention examples. A set of novel visualisations was created by *investigating and representing pedestrian behaviour* through an observational qualitative study. Observed behaviours were translated into *a simulation of pedestrian interactions using agent-based modelling*, representing a variety of pedestrian crossing behaviours. The pedestrian simulation was used *as a design tool* to improve and reflect on the design interventions.

Qualitative video analysis of pedestrian behaviours and interactions is presented with an emphasis on the various ways of interpreting the patterns and flows between pedestrians and vehicles. I analysed video observations using interaction analysis techniques since they address nonverbal behaviours. These observational transcriptions served as the basis for creating visualisations that accurately and clearly depict pedestrian interactions and movements. These visualisations included three types: (1) trajectory mapping, (2) feedback loops and (3) behavioural sequence. The last two types are novel ways of representing the information from video recordings as previously transcriptions were used for this kind of study.

Simulating pedestrian interaction using agent-based modelling

The novelty of the agent-based modelling simulation of pedestrians lies in creating a comprehensive model for street-crossing behaviours incorporating the following features:

- Pedestrians **can** cross from any point on the street.
- Pedestrians **can** resolve conflicts based on the stage of their crossing.
- Pedestrians **can** make decisions about risk-taking before they start to cross.
- Pedestrians are differentiated into **types**, based on the findings from the video observation.

The first three factors impacted on the creation of different types of pedestrians. Technical innovation included that an agent framework is developed, based on the video observations.

Novel relation between video analysis and agent-based modelling

The originality of the research is also demonstrated through its methodology, in combining a qualitative and computational method. Using qualitative video observations and agent-based modelling together provides a comprehensive model of pedestrian behaviours and interactions. To my knowledge, this research offers the first example of conducting qualitative video observation to create a pedestrian agent framework derived from observational data.

This way of combining qualitative and computational tools makes another methodological contribution as well. The process of developing pedestrian agents has not followed a linear process. My iterative, reflective combination of video observation and modelling is similar to a second-order cybernetics framework for calibrating, intervening and spotting issues in the simulation, while making new discoveries in the video data in light of the modelling process.

The intervention implemented in this PhD aimed to introduce dynamic permeability by focusing on the localised changes of spatiotemporal characteristics in the street. While the dynamic aspect of the intervention describes its responsiveness, permeability is represented through the increased movement possibilities available to pedestrians. The interventions represent the first step towards a dynamic and responsive environment by fostering the "unplanned" events (or interactions) during the spatiotemporal negotiations that occur in the street environment.

Reflecting on the interventions is one of the primary aims of developing an agent-based simulation. By using simulation, I aimed to construct an artificial street environment that reacts to pedestrian behaviours and promotes the decisions pedestrians practice on the street. I implemented the principles of intervention in the simulation and reflected on their potential improvements through observing the virtual space and monitoring the interface information on the key features of risk-taking behaviour and crash numbers.

Theoretical Research Contributions

Previous epistemologies framed the city as a collection of artefacts containing more morphologic references and physical structures, which resulted in static structures defining the spaces (e.g. Lynch, 1964; Rossi, 1984). Later, urban planners such as Gehl (2010) ushered in a new era by incorporating social elements into the city. Currently, technological advancements are transforming these perspectives into new ways of thinking about urban spaces by integrating various technologies. Taking advantage of these changes, this study contends that the street environment is a changing, temporal, and dynamic system that affects the interactions of road users, specifically in this case pedestrians. My approach to these changes is to place pedestrians at the centre of this widespread integration of digital and physical frameworks. The research aims to provide pedestrian interventions that are dynamic, changing, temporal, and *responsive*. I add clarity about the question of what pedestrian interventions are, by synthesising existing literature and classifying it according to its spatial and temporal impacts.

This survey of literature on existing pedestrian interventions is presented, with examples ranging from traffic calming strategies to desire lines studies. The literature review of street interventions was integrated with a practice-oriented review of recent and current examples. From the combination of these investigations, I brought forward a new taxonomic map, that evaluates their spatiotemporal features: permeability and temporality. This map highlighted that the interventions which are responsive (dynamic) and permeable are underexplored in the literature.

This thesis presents a novel methodological approach to understanding pedestrians and the street environment. It combines the real-world observations of pedestrians with computational methods to identify the pedestrians' interactions and behaviours by considering agents in relation to their surroundings and situations they are in. The motivation for conducting such study stems from the intention to combine the strengths of both qualitative and computational methods when researching pedestrian behaviour: using both methods iteratively help to gain perspective and understand the behaviours through new insights.

Using qualitative video observations, I addressed how important, challenging and – most importantly – subtle issues related to pedestrian interactions can be considered. In this study, various types of pedestrian characteristics are defined first, and then behavioural modules are identified to create pedestrian simulation.

Potential beneficiaries of this research

This research aims to contribute to designing intelligent tools for mobility systems. The intended beneficiaries of this research are grouped in four sections: (1) researchers in design disciplines, (2) researchers in other disciplines, (3) companies and public sector bodies and (4) policy makers. Researchers in design disciplines such as urban design, intelligent mobility, interaction design and system design could investigate spatial design using the taxonomy of pedestrian interventions, experiment with different mobility behaviours and vehicle-pedestrian interactions using the simulation platform, and experiment with the mobility systems using a cybernetic framework. Other researchers could include transport planners who are interested in developing pedestrian behaviours in traffic simulators or agent-based modellers who are interested in incorporating qualitative observation study into their models. Companies and public sector bodies include organisations that provide planning and design services or consultancy for city and mobility solutions, as well as self-driving companies that research interactions between AV and pedestrians. Policymakers could be authorities that provide guidelines to local bodies on how to improve pedestrians' experiences in order to achieve their goals on improving the urban mobility.

The research contributes to design disciplines by first, introducing a computational technique, agent-based modelling, into the human-centred design process. The human-centred design process was applied to the simulation: (1) by identifying individual differences of each pedestrian in the modelling stage and (2) by challenging the existing constraints of the street with the goal of influencing behaviour and social structures of the street. This helped to establish a higher level of heterogeneity for pedestrian agents in the simulation and created a more realistic pedestrian simulation compared to others in the literature. Secondly, it contributes to design theory by conducting a design practice in an interdisciplinary way through the usage of a cybernetic framework for developing and analysing agent-based simulations. Thirdly, it introduces adaptive, interactive and responsive approaches to designing urban mobility systems by introducing responsive street interventions.

The research aimed to benefit other disciplines such as transport studies, urban mobility, agent-based modelling and pedestrian simulations. The thesis contributes to transport studies by studying the topics of pedestrian, vehicle and street from a pedestrian perspective rather than a vehicle or infrastructure perspective. The research contribution on urban planning and mobility is made through adaptive and responsive interventions and the idea of planning the mobility on the street through its dynamic characteristics. It also contributes to agent-based modelling and pedestrian simulations by drawing a complex and realistic pedestrian behaviour modelling through relying on qualitative video observations conducted in the field.

The pedestrian framework which shows working principles of pedestrian decision making through their movement on the street and the pedestrian simulation can help organisations working on safe implementation of autonomous vehicles by focusing on understanding pedestrian behaviours. The simulation provides a selection of behaviours and pedestrian characteristics that can help to test autonomous vehicles' logic and behaviours.

Additionally, the simulation can help policy makers and urban planners generate and test new ideas for spatial planning of the streets. It can be used as a participation tool for non-coding people when developing new and different urban environments by illustrating vehicular and pedestrian traffic and their interactions. It can also help to understand which implementations increase the safety of pedestrians while helping to understand underlying principles of the traffic yielding process. These contribute to the overarching aim of increasing the adoption of active mobility by improving pedestrian environments.

Chapter 9 References

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