WALK-SHARING - A SMARTER WAY TO IMPROVE PEDESTRIAN SAFETY AND SAFETY PERCEPTION IN URBAN SPACES

Zur Erlangung des akademischen Grades eines
DOKTORS DER INGENIEURWISSENSCHAFTEN (Dr.-Ing.)
von der KIT-Fakultät für
Bauingenieur-, Geo- und Umweltwissenschaften des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION
von
Debjit Bhowmick

Tag der mündlichen Prüfung: 14 April 2022
Referent: Prof. Dr.-Ing. Peter Vortisch
Korreferent: Prof. Dr.-Ing. Stephan Winter

Karlsruhe (2022)

WALK-SHARING - A SMARTER WAY TO IMPROVE PEDESTRIAN SAFETY AND SAFETY PERCEPTION IN URBAN SPACES

by

DEBJIT BHOWMICK

A thesis submitted in total fulfillment for
the joint doctoral degree of

Doctor of Philosophy (PhD in Engineering)
in the
Department of Infrastructure Engineering
Faculty of Engineering and Information Technology
The University of Melbourne

and

Doctor of Engineering (Dr.-Ing.)
in the
Department of Civil Engineering, Geo and Environmental Sciences
Karlsruhe Institute of Technology

April 2022

"You're a wizard, Harry."
— Rubeus Hagrid,
Harry Potter and the Philosopher's Stone by J.K. Rowling

Dedicated to my parents, whose endless sacrifices have made me what I am today.

Dedicated to my wife who, in the past four years, has believed in me more than myself.

ABSTRACT

Although walking has been proven to be beneficial for the physical and mental health of human beings, and has been shown to be a key to sustainable and liveable communities, its modal share has been gradually diminishing with rapid motorisation and urbanisation across the globe. Moreover, challenging walking environments discourage people from walking, especially in the case of walking for transport. Fear of crime has been cited as the most important barrier for which walking becomes unattractive at critical times of the day, even though walking might be convenient otherwise. Fear of crime influences people's choice of route and travel mode. It forces them to avail costlier alternatives, such as taking viable detours, or abandoning walking altogether and switching to alternative, usually motorised, modes of transport. Fear of crime reduces the overall walkability of an urban area, reduces the time spent on walking, and thereby disrupts the benefits that are offered by walking.

Traditional approaches aimed at reducing fear of crime in outdoor spaces, comprising of urban design improvements and infrastructural overhauls, are expensive, localised, involve significant time and human effort. Other, more recent, location and IT based approaches, involving safe route recommendation systems, suffer from heavy dependency on crime and other proxy data sources, and have been known to segregate communities by profiling socio-economic groups.

To overcome the challenges of the existing methods, this thesis introduces *walk-sharing*. Walk-sharing is a novel form of shared mobility, which is aims to encourage people to choose walking over alternative modes, when it is viable. As people feel safer walking with a companion as compared to walking alone, walk-sharing matches people with similar spatio-temporal interests who are willing to walk to their respective destinations. By ensuring companionship for pedestrians for a part or the entirety of their journey, walk-sharing improves active natural vigilance, thereby reducing their fear of crime. By reducing fear of crime while walking, walk-sharing has the potential to make walking more attractive, thereby improving its modal share for short-distance trips, and consequently, reduce motorised traffic, thereby reducing emissions and congestion.

This thesis discusses the fundamentals of walk-sharing, delineates its similarities and distinctions with existing shared forms of mobility, and proposes a conceptual model that is an abstract representation of a possible walk-sharing system. Based on the logic of the conceptual model, this thesis presents an agent-based simulation model to objectively measure the performance of walk-sharing under plausible scenarios. Using theoretical simulations, this thesis presents the sensitivity behaviour of the walk-sharing model, which also shows the logical efficacy of the model itself. Based on justified assumptions on human preferences, this thesis presents a simulation of walk-sharing on a university campus scenario, achieving up to 80% effectiveness in terms of safety improvement.

To gain knowledge about the actual preferences of the community about walk-sharing, this thesis presents a survey and its findings, which depict the spatio-temporal preferences, social preferences, and the overall likelihood of people towards participating in walk-sharing. This thesis finally presents a more sophisticated and grounded simulation of walk-sharing, calibrated using information about actual human preferences on walk-sharing from the survey. Results show that walk-sharing is up to 60% effective in terms of safety improvement, while exhibiting spatio-temporal costs that are within the preferable standards of the community.

Walk-sharing overcomes the drawbacks of the existing fear of crime reduction approaches by being proactive (independent of crime and proxy crime data), inexpensive (no requirement of major infrastructural modification or significant human effort), and is scaleable and transferable (can be applied anywhere, and can be easily accessed by the community given the abundance of smartphones). In an age of ubiquitous computing, internet of things, efficient location-based services and smartphones, walk-sharing could be the 'smart' solution that promotes walking as a safer mobility choice for spatio-temporally convenient trips, and consequently progress towards more sustainable urban living, by increasing active mobility and reducing motorised traffic.

ZUSAMMENFASSUNG

Fortbewegung zu Fuß ist nachweislich der körperlichen und geistigen Gesundheit der Menschen zuträglich und gilt als Schlüssel zu nachhaltigem und lebenswertem städtischem Leben. Der Anteil der Fußgänger am Verkehrsaufkommen ist allerdings mit der rasanten Motorisierung und Verstädterung auf der ganzen Welt rückläufig. Darüber hinaus halten fußgängerunfreundliche Umgebungen Menschen davon ab, zu Fuß zu gehen. Die Angst vor Kriminalität wurde als wichtigstes Hindernis genannt. Sie macht das Zufußgehen zu kritischen Tageszeiten unattraktiv, selbst wenn es nach allen anderen Maßstäben bequem wäre. Die Furcht vor Kriminalität beeinflusst die Wahl des Weges und der Verkehrsmittel. Sie motiviert die Menschen dazu, kostspieligere Alternativen zu nutzen, zum Beispiel sinnvolle Umwege zu gehen oder ganz auf das Gehen zu verzichten und auf andere, meist motorisierte Verkehrsmittel umzusteigen. Die Angst vor Kriminalität verringert die allgemeine Begehbarkeit eines Stadtgebiets, reduziert die Zeit, die zu Fuß verbracht wird, und verhindert damit die Vorteile, die das Zufußgehen geboten hätte.

Herkömmliche Ansätze zur Verringerung der Furcht vor Kriminalität in Außenbereichen umfassen städtebauliche Verbesserungen und Infrastrukturüberholungen. Sie sind teuer, lokal begrenzt und erfordern einen erheblichen Zeit- und Personalaufwand. Andere, neuere, ortsgestützte IT-Ansätze, die zum Beispiel sichere Routenempfehlungssysteme beinhalten, leiden unter einer starken Abhängigkeit von Kriminalitäts- und anderen Daten und sind dafür bekannt, dass sie Gesellschaften durch die Erstellung von Profilen sozioökonomischer Gruppen segregieren.

Um die Herausforderungen der bestehenden Methoden zu überwinden, wird in dieser Arbeit das Walk-Sharing (wörtlich: gemeinsames Gehen) eingeführt. Walk-Sharing ist ein neuartiger Service in der Kategorie der geteilten Mobilität, die darauf abzielt, Menschen dazu zu ermutigen, zu Fuß zu gehen, anstatt andere Verkehrsmittel zu nutzen, wenn dies möglich ist. Da sich Menschen sicherer fühlen, wenn sie in Begleitung gehen, bringt Walk-Sharing Menschen mit ähnlichen räumlichen und zeitlichen Mobilitätsbedürfnissen zusammen, die bereit sind, zu Fuß zu ihren jeweiligen Zielen zu gehen. Durch das gemeinsame Gehen für einen Teil oder die gesamte Strecke verbessert das Walk-Sharing die aktive natürliche Wachsamkeit und verringert so die Angst vor Kriminalität. Durch die Verringerung der Angst vor Kriminalität während des Gehens hat Walk-Sharing das Potenzial, das Gehen attraktiver zu machen und damit den Anteil des Fußverkehrs auf kurzen Strecken zu erhöhen und folglich den motorisierten Verkehr zu reduzieren, was wiederum zu einer Verringerung der Emissionen und der Verkehrsbelastung führt.

In dieser Arbeit werden die Grundlagen des Walk-Sharing erörtert, seine Gemeinsamkeiten und Unterschiede zu bestehenden geteilten Mobilitätsformen herausgearbeitet und ein konzeptionelles Modell vorgeschlagen, das eine abstrakte Darstellung eines möglichen Walk-Sharing-Systems darstellt. Basierend auf der Logik dieses konzeptionellen Modells wird in dieser Arbeit ein agentenbasiertes Simulationsmodell vorgestellt, um die Leistung von Walk-Sharing unter plausiblen Szenarien objektiv zu messen. Anhand theoretischer Simulationen wird das Sensitivitätsverhalten des Walk-Sharing-Modells dargestellt, was auch die logische Funktion des Modells selbst zeigt. Danach werden begründeter Annahmen über menschliche Präferenzen herangezogen, um eine Simulation des Walk-Sharing auf einem Universitätscampus vorzustellen. Diese Simulation zeigt bis zu 80% Effektivität in Bezug auf die Verbesserung der Sicherheit.

Schließlich werden in dieser Arbeit eine Umfrage und deren Ergebnisse vorgestellt, die die tatsächlichen räumlich-zeitlichen Präferenzen, die sozialen Präferenzen und die allgemeine Wahrscheinlichkeit der Teilnahme an Walk-Sharing aufzeigen. Mit diesen Erkenntnissen wird eine kalibrierte, ausgefeiltere und fundiertere Simulation des Walk-Sharing vorgestellt. Die Ergebnisse zeigen, dass gemeinsames Gehen bis zu 60% zur Verbesserung der Sicherheit beiträgt und gleichzeitig räumlich-zeitliche Kosten verursacht, die im Rahmen der von der befragten Gruppe bevorzugten Standards liegen.

Walk-Sharing überwindet die Nachteile der bestehenden Ansätze zur Verringerung der Kriminalitätsfurcht, indem es proaktiv (unabhängig von Kriminalitäts- und stellvertretenden soziodemographischen Daten) und kostengünstig ist (keine größeren infrastrukturellen Veränderungen oder erheblicher menschlicher Aufwand erforderlich). Es ist skalierbar und übertragbar (kann überall angewendet werden und ist für die Gesellschaft angesichts der gegenwärtigen Verbrei-

tung von Smartphones leicht zugänglich). Im Zeitalter des ubiquitären Computings, des Internets der Dinge, effizienter standortbezogener Dienste, und Smartphones könnte Walk-Sharing die intelligentere Lösung sein, die das Zufußgehen als sicherere Mobilitätsform für räumlich und zeitlich günstige Wege fördert und somit Fortschritte in Richtung eines nachhaltigeren städtischen Lebens macht, indem sie die aktive Mobilität erhöht und den motorisierten Verkehr reduziert.

DECLARATION

I, Debjit Bhowmick, declare that this thesis titled, 'Walk-sharing - A smarter way to improve pedestrian safety and safety perception in urban spaces' and the work presented in it are my own. I confirm that:

- The thesis comprises only my original work towards the total fulfilment of the joint doctoral degree - *Doctor of Philosophy (Ph.D.)* from The University of Melbourne, and *Doctor of Engineering (Dr.-Ing.)* from Karlsruhe Institute of Technology, except where indicated in the preface;
- the main content of some chapters are largely derived from published manuscripts of which I am the first author;
- due acknowledgement has been made in the text to all other material used; and
- the thesis is fewer than 100,000 words excluding tables, bibliographies and appendices.

Debjit Bhowmick
April 2022
Melbourne, Australia

PREFACE

This thesis presents the work that I, Debjit Bhowmick, the author of this thesis, carried out during my joint-doctoral candidature at the Department of Infrastructure Engineering, The University of Melbourne and Department of Civil Engineering, Geo and Environmental Sciences, Karlsruhe Institute of Technology. The research described in this thesis was supervised by Prof. Stephan Winter (The University of Melbourne), Prof. Mark Stevenson (The University of Melbourne) and Prof. Peter Vortisch (Karlsruhe Institute of Technology).

My tasks during my doctoral candidature were developing research ideas from extensive literature review, defining the research problem, formulating research questions, designing and implementing methods to answer these research questions, and writing the thesis. My supervisors have helped me at every stage of my research including planning the overall development of the work presented in this thesis, participating in defining the research problems, suggesting relevant research materials, and providing technical feedback regularly via weekly progress meetings.

In the following, the publications included in this thesis are listed, which have been published by me, the author of this thesis, during my doctoral candidature. The ideas and developments presented in this thesis have been partly published in these articles. The chapters of this thesis which uses these published research articles, clearly state the same at the beginning.

Bhowmick, Debjit, Stephan Winter, Mark Stevenson, and Peter Vortisch (2021a). "Exploring the viability of walk-sharing in outdoor urban spaces." In: *Computers, Environment and Urban Systems* 88.101635, p. 15. ISSN: 0198-9715. DOI: 10.1016/j.compenvurbsys.2021.101635.

— (2021b). "Investigating the practical viability of walk-sharing in improving pedestrian safety." In: *Computational Urban Science* 1.21, p. 22. ISSN: 2730-6852. DOI: 10.1007/s43762-021-00020-z.

During my doctoral candidature, I have also published research related to pedestrian mobility in outdoor urban spaces, which have not been included in this thesis. These articles are listed below.

Bhowmick, Debjit, Stephan Winter, and Mark Stevenson (2019). “Comparing the costs of pedestrian wayfinding heuristics across different urban network morphologies.” In: *GeoComputation 2019*. Queenstown, New Zealand. DOI: `10.17608/k6.auckland.9846137.v2`.

— (2020). “Using Georeferenced Twitter Data to Estimate Pedestrian Traffic in an Urban Road Network.” In: 11th *International Conference on Geographic Information Science (GIScience 2021) - Part I*. Vol. 177, 1:1–1:15. DOI: `10.4230/LIPIcs.GIScience.2021.I.1`.

Bhowmick, Debjit, Stephan Winter, Mark Stevenson, and Peter Vortisch (2020). “The impact of urban road network morphology on pedestrian wayfinding behaviour.” In: *Journal of Spatial Information Science* 21, pp. 203–228. DOI: `10.5311/JOSIS.2020.21.601`.

"There's no Hogwarts without you, Hagrid."
— Harry Potter, Harry Potter and the Chamber of Secrets by J.K. Rowling

ACKNOWLEDGMENTS

When I started my PhD back in 2018, little did I know about the journey that I was about to embark on. But, the preparations had started months before that. Leading up to May 2018, when my candidature started, I had already completed a lot of 'firsts' in my life within a short span of time. I had left my first job, I got married, I had travelled overseas for the first time, and most importantly, I was about to start a PhD. Understandably, it was an overwhelming experience for me, and I needed every bit of technical and moral support from people around me to pursue this intriguing journey. In what follows, I make a sincere effort to thank each and every one of those people, without whom, this journey would have been unbearable, if not impossible.

On the technical front, I express my profound gratitude towards my doctoral supervisors, Prof. Stephan Winter, Prof. Mark Stevenson and Prof. Peter Vortisch, for their sincere efforts in guiding me through the plethora of technical challenges that I had encountered during my PhD. It was my privilege to be regularly in the presence of such prominent researchers. Their expertise and constant guidance helped me conduct research with conviction. All the credit for my growth as a researcher goes to them. I specially thank Stephan for his promptness, astuteness and altruism while performing his supervisory duties.

I would also like to thank my peers at the university who always presented themselves wholeheartedly when I needed their help. Unni Krishnan was a constant source of inspiration, support (and gossip) at times of need, especially over a cup of bubble tea. Subhrasankha, my neighbour at the office, selflessly devoted time to address my technical problems, while providing moral support at times of need. The evening walks and table tennis sessions with Abhisek, Dibbendu, Sapan and Joydip were more relaxing than even the most expensive spa treatments Melbourne had to offer. Thanks to Masoud, I regularly got an oppurtunity to brush up on my football lingo. Debaditya was

like an elder brother who gave me salient advice when I needed it the most. Santa, Ehsan, Ivan, Kimia, David, Wenyan, Kiersten, Saroj, Marko, Kamal, Rajesh, Zahlan, Hang, Xiaonan and Desmond provided the much needed light-hearted conversations during work-hours.

Back home in India, there were friends who made every effort to engage with me over digital media. Angshuman has never missed an opportunity to discuss cricket, even if that meant sacrificing several hours of sleep. Tushar, Kuntal, Subhankar and Subhaprasad ensured that the Sunday trivia nights ran regularly during lockdown, the highest points of my weeks in those difficult times, undoubtedly. Sourav, Arnab, Aritra and Rahul, my neighbours back home, always had words of consolation when I was feeling homesick.

My family back home are the only people in this acknowledgement who have missed me more, than I have missed them. My acknowledgement towards my parents cannot be limited to these past four years. They have made endless sacrifices throughout their life, so that I could become someone prominent at somewhere important, and for this, I will forever be indebted to them. All my academic achievements are a result of those countless selfless deeds, and hence, I dedicate this thesis to the both of you. I missed several important landmarks of my younger sibling Aishi, but she never missed a chance to catchup with me over hilarious memes. My in-laws have been no less than my parents in terms of extending their moral support during times of crisis. To quote the famous Disney feature film, Lilo and Stitch, "*Ohana means family. Family means nobody gets left behind or forgotten*". I thank you all from the bottom of my heart.

Finally, I take this opportunity to thank my wife Anwesha, who in these past four years, have been no less than the most important co-author of my journey. I have probably never explicitly appreciated your role in this PhD journey, but it is about time I do. Being the wife of a doctoral student is a daunting challenge not many are prepared to take, but you have surpassed all odds with flying colours. You have always negated any despondence in my academic life with your cheerfulness and love. Your unending support and perennial motivation was what drove me through this stress-filled roller coaster journey. Despite the omnipresent disagreements, you have always stood by me, and have always been my biggest fan with the loudest cheer. My arrival at the finish line was only possible because of the sacrifices you have made to accommodate my path to success. Thank you!

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1

INTRODUCTION

*This chapter is partially (Section 1.1 and Section 1.2) based on the introduction sections of the manuscripts "**Exploring the viability of walk-sharing in outdoor urban spaces**" published in* Computers, Environment and Urban Systems *and "**Investigating the practical viability of walk-sharing in improving pedestrian safety**" published in* Computational Urban Science, *both authored by Bhowmick, Winter, Stevenson and Vortisch (2021). My contribution as the first author of these manuscripts includes proposing the hypothesis and the research problem, designing a systematic literature review method, analysing the results and presenting the discussions and conclusion. These works were supervised by Prof. Stephan Winter (my primary supervisor at The University of Melbourne), Prof. Mark Stevenson (my co-supervisor at The University of Melbourne), and Prof. Peter Vortisch (my primary supervisor at Karlsruhe Institute of Technology) who provided feedback and suggestions at every stage of these studies.*

1.1 BACKGROUND

Walking is the most common mode of travel given its high levels of accessibility, especially for short trips (Hong and Chen, 2014; Zielstra and Hochmair, 2012). Apart from being an independent mode of transport, walking also serves as the most common mode of access to public transport (Bassett et al., 2008), as well as private transport such as parked cars, motorcycles and bikes. Researchers have suggested that walking has significant health co-benefits, and studies have shown that walking improves people's physical health by preventing diseases (Giles-Corti et al., 2016; Warburton, Nicol, and Bredin, 2006). Others have shown the positive impacts of walking with respect to a person's mental health (Besser and Dannenberg, 2005; Donnelly et al., 2000; Johansson, Hartig, and Staats, 2011; Lee and Buchner, 2008). Among 18-to-24-year-old Australians, walking for transport alone accounts for 48 % of their total physical activity (Garrard, 2017).

Walking, as an active travel mode, has community benefits as well. As destination-focused walking increases, the use of motor vehicles goes down for trips that would otherwise be convenient for walking (e. g., trip to the nearby grocery store, trip to the nearest transit facility). This consequently reduces traffic congestion, energy consumption, air and noise pollution, the overall level of traffic danger, and other related expenses (Pucher and Buehler, 2010; Stevenson et al., 2016). All of this, in turn, offers more liveable communities with more efficient short errand trips and economic benefits to local business and real estate (Zhang and Mu, 2019).

However, challenging walking environments discourage people from walking. Inconvenience acts as the major challenge for outdoor walking. For example, lengthy commutes or walking in adverse weather conditions is never a convenient option, and therefore people always seek alternative modes for travel in such inconvenient circumstances. But, even under convenient circumstances, certain aspects of the built environment leave pedestrians feeling fearful or unsafe and thus discourage people from walking outdoors (Colls and Evans, 2013; Ferrer and Ruiz, 2018; Ferrer, Ruiz, and Mars, 2015; Nasar, 1990; Powdthavee, 2005; Ross, 2000; Sakip, Johari, and Salleh, 2012). This stems from the physical vulnerability of pedestrians who travel with lower speeds and are in an unprotected state as compared to other travel modes (Wegman, Aarts, and Bax, 2008). Existing studies have shown that personal safety is a key concern for pedestrians in the urban context (Doeksen, 1997; Halat et al., 2015; Warr and Ellison, 2000).

Popular studies on walkability and walking behaviour have considered people's safety perception to be a crucial factor in assessing the walkability of a neighbourhood (Clifton and Livi, 2005; Gilderbloom, Riggs, and Meares, 2015; Pain, 2001; Yin, 2013; Zhang and Mu, 2019). Safety perception of people determines their social well-being and hence, their mobility behaviour (Colls and Evans, 2013; Powdthavee, 2005). More than actual crime, fear of crime has been cited as the most important barrier for which walking becomes unattractive at critical times of the day, even though walking might be convenient otherwise (Ferrer and Ruiz, 2018). It prevents pedestrians, mostly women and the elderly, from walking in public places after dark or alone (Franc and Sucic, 2014; Garrard, 2017).

In Chicago, Illinois, fear of victimisation has been found to reduce the likelihood of outdoor walking (Ross, 2000). Over a-third of Australians do not feel safe when walking home alone at night (Jericho, 2017). In the U.S., around 50% of women and 20% of men said that they are afraid to walk in their own neighborhoods at night alone (Badger, 2014). In another survey, 71% of elementary school students perceived their school routes to be dangerous, while 77% of them showed concerns about street gangs (Meyer and Astor, 2002). Another study had found that students are five times more likely to experience violent crime while in transit to and from school, as compared to being in school (Lemieux and Felson, 2012).

People's perception of safety (fear of crime) may not reflect actual safety from crime (Park et al., 2011). Seemingly fearful places do not necessarily coincide with crime hotspots, or locations with a history of criminal incidents. This has been proven by studies establishing a disjunction of this sort between fear of crime and crime (Davis and Dossetor, 2010; Rountree and Land, 1996). Moreover, since fear of crime is subjective in nature, a location perceived as safe by one, could be deemed as unsafe by another. Crime locations are usually very few in number, especially when compared to the number of locations where people experience fear of crime. Pedestrians may feel vulnerable in many places besides such locations. Being fearful while walking, reasonably or unreasonably, results in harmful effects on both the individual and the community (De Silva, Warusavitharana, and Ratnayake, 2017; Nasar, 1983).

Pedestrian route and travel mode choice is often influenced by fear (Rodríguez et al., 2015). Pedestrians feeling vulnerable while walking alone, opt for viable detours along the way to their destination, to avoid places they perceive as unsafe, or where they may feel vulnerable (Borst et al., 2009; Michael, Green, and Farquhar, 2006; Park et al., 2011; Pun-Cheng and So, 2019). Apart from taking viable detours, this fear of victimisation often leads pedestrians to avail costlier alternatives, such as abandoning walking altogether and switching to alternative forms of transport (Ferrer and Ruiz, 2018; Hong and Chen, 2014). Thus, the fear of victimisation reduces the appeal of walking. The existence of seemingly feared places reduces the overall walkability of an urban area, reduces the time spent on walking (De Silva, Warusavitharana, and Ratnayake, 2017), and thereby disrupts the benefits that are offered by walking (Ross, 1993; Taylor, 1987). Moreover, it promotes motorised traffic which negatively impacts the liveability of urban areas.

1.2 MOTIVATION

While traditional approaches aimed at reducing *fear of crime* amongst pedestrians, such as improvements in urban design, or installation of street furniture, have been employed over decades, they are usually costly, never holistic, and take significant time before coming into effect (Day, Anderson, Powe, McMillan, and Winn, 2007; Ferrer, Ruiz, and Mars, 2015; Fisher and Nasar, 1992; Fotios and Castleton, 2016; Painter, 1994, 1996). Other, more recent and less traditional approaches, such as safe route recommendation systems, or crowd-sourced safety ratings of places, have some major drawbacks, such as dependency on historical crime records or proxy social media data which often misrepresents feelings of fearfulness at places (Fu, Lu, and Lu, 2014; Kim, Cha, and Sandholm, 2014; Utamima and Djunaidy, 2017). With the advancement of technology, ubiquitous computing and smartphone sensors, this thesis looks at tackling the challenge of reducing fear of crime with a smarter approach.

Existing literature suggests that the absence of people is the major reason for pedestrians feeling fearful while walking through urban spaces at critical times of the day, even when elements of the infrastructure are conducive for walking (e. g., good sidewalk condition, sufficient street lighting) (Ferrer and Ruiz, 2018). Pedestrians feel safer when they walk with a companion as compared to walking alone in environments perceived as unsafe (Clifton and Livi, 2005). The presence of just one other pedestrian nearby boosts natural vigilance. From the pedestrian's perspective, security increases, perceived risk reduces significantly and so does the fear of victimisation (Cohen and Felson, 1979). From the perspective of an offender, the presence of other pedestrians nearby is not favourable as it increases the chances of being recognised or interrupted (Iglesias, Greene, and Dios Ortúzar, 2013; Painter, 1994). Hence, a person could opt for walking when they share their walking trip with a trustworthy walking companion, such as a friend, a colleague, or a family member, as they feel safer. But, it cannot be guaranteed that a pedestrian will have another known pedestrian for mutual companionship under all possible conditions of space-time. To overcome this challenge, this thesis proposes ***walk-sharing***, a cost-effective and proactive approach to improve pedestrian safety.

Walk-sharing is a proposed novel form of shared mobility, where potential pedestrians get matched to each other and would share their walking trip. This would ensure a walking companion, albeit unknown, and thus encourage people to choose walking over alternative modes, when it is viable. Walk-sharing thus overcomes fear of crime in pedestrians that arises out of seemingly unsafe walking environments, by making them walk in company instead of walking alone. The presence of another person in proximity not only reduces fear of crime, but also reduces the likelihood of victimisation by boosting natural vigilance, especially in sparsely populated outdoor environments at critical times of the day. Under high levels of ambient pedestrian population, people may not feel the need for availing walk-sharing due to the high level of natural vigilance already present. But in sparsely populated environments, presence of people walking at the same time along the entirety of the same route cannot be guaranteed. Walk-sharing makes an attempt to ensure such spatio-temporal overlap between at least two pedestrians so that they can walk together while trying to optimise related costs (e. g., waiting time, detour length) for both.

This novel intervention is aimed at reviving the appeal of walking as a travel mode even at critical times of the day, and the benefits that should follow thereafter. This intervention, unlike others, is relatively inexpensive, as it does not require municipal authorities to incur significant costs to revamp street furniture. It is also a 'proactive' method for improving both safety and security of pedestrians, meaning that unlike existing reactive methods, it is independent of historical crime records, or any other proxy data that attempts to represent fear of places among pedestrians. It is also a more inclusive approach, as it does not create ghettos by asking people to avoid certain locations. In principle, walk-sharing has the ability to reduce both fear of crime and crime itself.

1.3 HYPOTHESIS AND RESEARCH QUESTIONS

The *overall hypothesis* of this thesis is that **walk-sharing can serve a significant portion of the community by significantly improving the safety and safety perception of pedestrians, thereby elevating the attractiveness of walking (encouraging people to walk when viable without personal safety concerns) even at critical times of the day**

(hours when pedestrians feel vulnerable and prefer a companion to walk with), with acceptable levels of costs (ones that are critical in walk-sharing). Here, the *overall objective* is to **formulate a theoretical understanding of walk-sharing, investigate its community acceptance, and investigate whether walk-sharing will be a viable alternative to reduce fear of crime and thereby improve pedestrian safety and safety perception.** In this thesis, the acceptability of walk-sharing is investigated in multiple stages. Each stage, equivalent to a chapter in this thesis, is briefly described as follows, based on its corresponding research questions.

1. **Fundamentals of walk-sharing (Chapter 3)**: The primary objective of this chapter is to outline the fundamentals of walk-sharing. The scope includes stating the core concepts of walk-sharing, defining the costs of walk-sharing which are later used to measure its performance, understanding the factors that would be critical to the performance of walk-sharing, and proposing a conceptual model of walk-sharing. The following research questions are addressed:
    a) How can a walk-sharing system be designed?
    b) While the benefits of walk-sharing are apparent, what are the factors that could serve as possible deterrents (costs) of walk-sharing?
    c) What are the factors that will be critical to the performance of walk-sharing?
2. **Exploring the technical viability of walk-sharing (Chapter 4)**: The primary objective here is to understand whether walk-sharing can be technically (theoretically) viable in a real-world scenario. The scope includes converting the proposed conceptual model into an agent-based simulation model for the purpose of objectively measuring the performance of walk-sharing, running simulations with synthesised data using this agent-based model to prove the logical validity of the conceptual model, and then testing the performance of walk-sharing in a real-world scenario. The following research questions are addressed:
    a) How sensitive are the costs of walk-sharing to varying levels of pedestrian demand and other critical factors representing spatio-temporal preferences of pedestrians?

   b) Will walk-sharing be technically viable in a real-world scenario?

3. **Community preferences on walk-sharing (Chapter 5)**: Here the objective is to investigate how the community perceives walk-sharing. Given that the effectiveness of walk-sharing is largely dependent on its community acceptance, the scope of this stage of the thesis includes conducting a web-based survey that asks respondents to state their preferences on walk-sharing. Another objective was to understand whether demographics of the respondents played a part in governing their choices. More specifically, the following research questions are addressed:
   a) What is the likelihood of walk-sharing uptake in the community?
   b) What is the extent of spatio-temporal compromises that people are willing to make to avail walk-sharing?
   c) Are there any social preferences related to choice of walking companion that may affect the uptake of walk-sharing?
   d) Do socio-demographic characteristics influence the preferences of people related to walk-sharing?
4. **Investigating the practical effectiveness of walk-sharing in improving pedestrian safety (Chapter 6)**: Here the objective is to derive the practical viability and effectiveness of walk-sharing using previously defined performance metrics (waiting time, detour distance, walk-alone distance and matching rate) and consequently investigate the effectiveness of walk-sharing in terms of its major objective of improving pedestrian safety and safety perception. This is done by calibrating the existing walk-sharing model using informed choices of spatio-temporal and social parameter thresholds and/or their distributions, as derived from the survey conducted in the previous stage. The following research question is addressed:
   a) To what extent can walk-sharing practically improve pedestrian safety and safety perception in a real-world urban scenario?

All these stages i. e., *walk-sharing fundamentals, its viability, its community acceptance, and effectiveness in improving pedestrian safety perception* collectively help in addressing the overall hypothesis of this thesis, .

1.4 CONTRIBUTIONS

Figure 1 shows the logical flow of the studies included in this thesis. The thesis contributes towards the understanding of whether walk-sharing is an effective intervention that can reduce fear of crime and thereby improve safety perception among pedestrians significantly, while remaining viable in terms of its associated costs. The contributions at each stage of this thesis are stated in the following paragraphs.

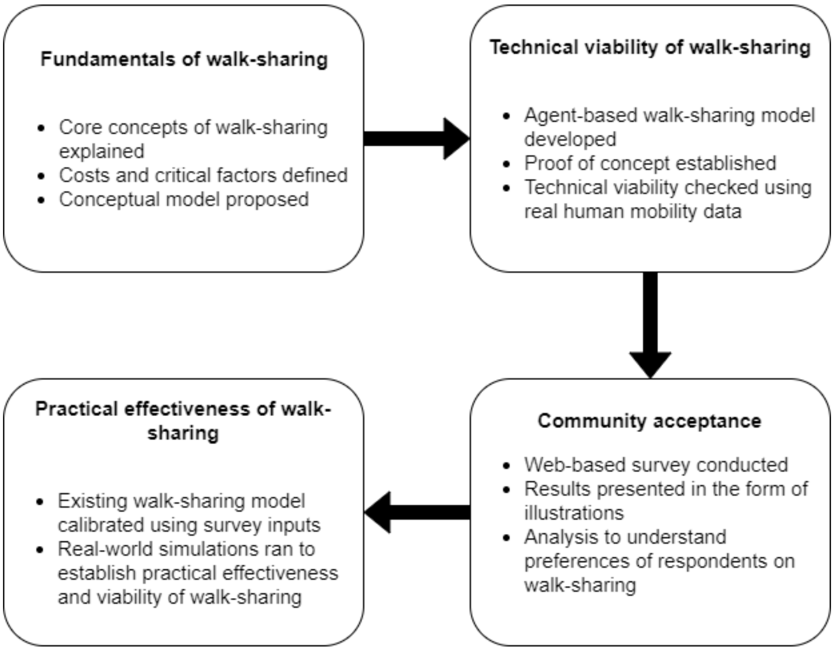

Figure 1: Logical flow of the major contributions of this thesis

The **first contribution** of this thesis is the novel concept of walk-sharing, a smart intervention in an age of seamless connectivity, to reduce fear of crime among pedestrians. Walk-sharing surpasses the traditional and other more recent approaches (discussed in detail in Chapter 2) by being proactive, less data-driven, scaleable and transferable. This contribution includes introducing walk-sharing and its conceptual model, understanding its benefits, costs and critical factors that drives its performance.

The **second contribution** of this thesis is the establishment of the technical viability of walk-sharing in a real-world scenario. This contribution includes development of an agent-based simulation model, checking for the sensitivity of the costs of walk-sharing (objective performance metrics) against the critical factors under plausible scenarios via theoretical simulations, and testing the walk-sharing model with real-world human mobility data.

The **third contribution** of this thesis is knowledge on the community acceptance of walk-sharing. This involved gathering information from the public on their perceptions on walk-sharing, if it was implemented in future. This included answering questions such as how likely would they be to avail walk-sharing, or what their spatio-temporal and social preferences would be. Consequently, the analysis of survey responses aimed to gain deeper insights on the distributions of the responses to each perception and preference, and understand whether these are governed by the socio-demographics of the respondents.

The **fourth and final contribution** of this thesis is inferring the practical effectiveness of walk-sharing in terms of safety improvement for pedestrians and therefore, establishment of the practical viability of walk-sharing in a real-world data-driven urban scenario by calibrating the existing walk-sharing model with parameter thresholds and distributions derived from the survey. This way the practical viability of walk-sharing could be objectively measured using relevant performance metrics viz., waiting time, detour length, walk-alone distance, matching rate, and and practical effectiveness in improving pedestrian safety using safety index.

1.5 THESIS STRUCTURE

The remainder of the thesis is organised as follows.

Chapter 2 presents a detailed literature review of the studies that form the background of this thesis. This chapter highlights the existing challenge of fear of crime among people in relation to walking, and how it negatively impacts pedestrian mobility decisions in urban scenarios. It presents the the existing approaches that attempt to improve safety perception of pedestrians and consequently, their walking experience. The chapter then explains that walking alone or walking in the absence of nearby pedestrians is as important as other, more well-researched factors that influence fear of crime. It discusses the existing passive and active approaches that aim to address this challenge of reducing walking alone at critical hours of the day, and states their limitations. It cites studies to argue that walking alone or walking without other pedestrians nearby, is a challenge that needs to be resolved using a smarter active vigilance approach. As walk-sharing is a potential new addition to the developing and rapidly growing universe of shared mobility, this chapter discusses literature related to shared mobility to understand the similarities and distinctions between walk-sharing and the existing forms of shared mobility.

Chapter 3 states the fundamentals of walk-sharing. It introduces the novel intervention of walk-sharing, showcases a conceptual model of walk-sharing, defines its costs and finally identifies relevant critical factors that would significantly govern these costs.

Chapter 4 discusses the study to investigate the technical viability of walk-sharing. It presents algorithms that are used to realise the conceptual model of walk-sharing into an agent-based simulation model. This agent-based model of walk-sharing is used to objectively measure the performance of walk-sharing, and thereby deduce its technical viability using real-world mobility data.

Chapter 5 discusses the web-based survey that was conducted to study public perception about walk-sharing. It includes presentation of survey results using illustrations, estimating the likely uptake of walk-sharing, understanding spatio-temporal and social preferences of the respondents, and to understand the role of socio-demographic variables with the stated preferences.

Chapter 6 presents the investigation of practical effectiveness and viability of walk-sharing using objective measures of performance of walk-sharing. The chapter presents calibration of the existing walk-sharing model using information obtained from the survey. The calibrated model then quantifies the effectiveness of walk-sharing in terms of improving safety and safety perception of pedestrians in a real-world urban scenario, while checking for the resultant levels of associated costs.

Chapter 7 concludes this thesis by stating the scientific contributions of this thesis, critically reflecting upon the major findings of the studies, stating the limitations of the proposed approaches as well as the scope of future research directions, and finally sharing the vision for walk-sharing in terms of finding a suitable place in existing and future urban mobility systems.

2

LITERATURE REVIEW

This chapter reviews the relevant literature that serves as the background and motivation of the research presented in this thesis. Section 2.1 discusses about fear of crime among pedestrians being a prominent challenge in outdoor urban spaces, even in the developed countries of the world. Section 2.2 discusses studies that have shown that fear of crime and safety perception among pedestrians influence their mobility decisions. Section 2.3 discusses the existing approaches that are present in the literature that attempt to improve safety perception of pedestrians and consequently, their walking experience. Section 2.4 explains that walking alone or walking in the absence of nearby pedestrians is as important as other, more well-researched factors influencing fear of crime among pedestrians. It also discusses the existing passive and active approaches that aim to address this challenge of reducing walking alone at critical hours of the day, and states their limitations. Finally, Section 2.5 presents literature related to shared forms of mobility due to fundamental similarities between the structural elements of existing shared mobility forms and the proposed novel concept of walk-sharing.

2.1 FEAR OF CRIME IN PEDESTRIANS

Fear of crime or criminal victimisation is a major challenge in the urban context. Fear of crime first emerged as an area of academic enquiry in the 1970s and has remained an area of concern, even in high-income countries (Lloyd-Sherlock, Agrawal, and Minicuci, 2016). Policymakers and researchers have concerned themselves heavily over the subject of fear of crime among pedestrians in the last decade (Roberts, 2014). Gilchrist et al. (1998) had concluded that *"such fear continues to impinge upon the well-being of a proportion of the population"*. Since the 1960s, researchers have examined the safety perception of individuals walking in their local area during night time (Roberts, 2014).

Ross (1993) conducted a survey with a representative national sample of 2031 adults, aged 18 to 90 years, across United States households in 1990. She found evidence that psychological distress caused by fear of crime resulted in limited walking behaviour among respondents. In other words, fear of crime was found to reduce the likelihood of outdoor walking. Jericho (2017) reviewed OECD's (Organisation for Economic Co-operation and Development) Better Life Index. He stated that *"Despite very good results on life expectancy, personal health and the homicide rate, only 63.6% of Australians feel safe when walking home at night"*. Foster et al. (2014) examined the influence of fear of crime on walking using a longitudinal study design conducted in Australia. They found that for every one level increase in fear of crime (on a five-point Likert scale), walking within the neighbourhood reduced by approximately 22 minutes/week per person. Roman and Chalfin (2008) studied 901 randomly selected individuals living in 55 neighbourhoods in Washington D.C. in a survey conducted in 2005. Their results indicated a negative association between fear of crime and outdoor walking. A comparative survey in four countries conducted by Plan International Australia and Our Watch survey (2016) revealed that a majority of respondents agree with the statement *"girls should not be out in public places after dark"*. Results from surveys conducted by Gallup and the National Opinion Research Center (NORC) General Social Surveys (GSS) spanning over four decades have revealed that over a third of the respondents have fears of criminal victimisation when walking alone at night (Roberts, 2014).

Some studies discussed how the perception of safety varies across pedestrian characteristics. Pain (2001) attempted to address the complexity of the relationships between fear of crime in the city with age, race and gender. It showed how the perception of safety among people varied across environments, and how the perception of safety at certain environments varied across age, race and gender. Clifton and Livi (2005) studied the potential gender differences regarding walking behavior, attitudes about walking and perceptions of the environment, including safety, in three Maryland communities with different walkability and socioeconomic characteristics. The study found fear of crime as one of the major factors influencing walking behaviour, especially among women. Roman and Chalfin (2008) found that women and the elderly reported significantly higher levels of fear of crime which limited their outdoor walking.

2.2 INFLUENCE OF FEAR OF CRIME ON HUMAN MOBILITY BEHAVIOUR

Human mobility behaviour has been found to be significantly affected by fear of crime in outdoor spaces. It (a) negatively affects route choices of pedestrians, (b) forces them to switch modes of transport and (c) limits their activities by increasing mobility constraints.

2.2.1 *Fear of crime and pedestrian route choice*

Borst et al. (2009) collected data concerning the walking route choice to specific destinations reported by 364 independently living elderly residents (55–80 years) from three Dutch urban districts. They found that the elderly in the Netherlands tend to walk along the boundary of a park instead of walking across it, that they also avoid streets which are concealed by green elements such as large trees, and that they tend to avoid streets which are sparsely populated by perceiving them as unsafe. Evers et al. (2014) indicated that parents perceived streets with trees as unsafe for their children. Rodríguez et al. (2015) conducted a study on adolescent girls in San Diego by analysing their GPS trajectories and observed that the probability of selection of a route was proportional to its Safety Index. Mehta (2008) conducted a study in Boston, United States, using the data from surveys and interviews, which showed that people perceive major roads having non-residential properties, such as offices, amenities and stores to be safer and tend to follow such routes. Ferrer and Ruiz (2018) used a qualitative methodology to identify and compare factors of the built environment influencing pedestrians' decision to walk for short trips. They found that women in Valencia and Granada (two major cities in Spain) do not walk on roads with insufficient lighting at night as they feel such roads are unsafe and highly vulnerable to crime. Rasouli and Timmermans (2014) also indicated street lighting as the factor influencing route choice, and resulting in different routes for pedestrians at daytime and at night. Oakes, Forsyth, and Schmitz (2007) found that pedestrians tend to walk in areas which are crowded, especially at night, since it offers a sense of safety. Pun-Cheng and So (2019) used a questionnaire to identify a pedestrian's perception of the key variables of walkability, and a map survey to explore their actual route choice in two different districts (residential and commercial) in Hong Kong. They found that pedestrians prefer safer routes over faster routes, especially at night-time, and that pedestrians tend to walk along paths of high pedestrian flow and high brightness.

2.2.2 *Fear of crime and travel mode choice*

Lynch and Atkins (1988) conducted a survey to understand drivers of fear of crime among women in Southampton. They found that a personal vehicle such as a car was cited as the safest mode of transport by the respondents, while walking was cited as the least safe mode of travel. Loukaitou-Sideris (2004) stated that private automobiles are perceived as the safest means of transportation by women. Loukaitou-Sideris (2014) also conducted in-depth interview sessions with representatives of 16 national women's interest groups in the United States. She stated that fear of criminal victimisation leads people, mostly women, to utilize precautionary measures and strategies that affect their travel patterns. These include the adoption of certain travel modes and transit environments over others, such as minimising walking as it is deemed as more unsafe.

2.2.3 *Fear of crime and reduced mobility*

Keane (1998) found that fear of crime in outdoor urban spaces negatively influences their mobility behaviour and limits their activities significantly. Whitley and Prince (2005) analysed data from North London, United Kingdom, and found that fear of crime in individuals restricted their spatial and temporal movements, and had negative impacts on their overall mental health. Sallis et al. (2009) analysed a survey of physical activity data in Sweden. They found that older people, with a higher level of fear of crime, walk less. Ferrer, Ruiz, and Mars (2015) used a qualitative approach to identify built environmental factors that influence short walking trips and found that factors related to perceived safety from crime, such as absence of people and poor street lighting, as the most influential deterrent to walking. Gallagher et al. (2012) conducted a cross-sectional survey study that inferred that fear of crime influenced neighborhood walking patterns among older adults with limited mobility. Stafford, Chandola, and Marmot (2007) studied more than 10,000 London-based civil servants aged 35 to 55 years. They found evidence that fear of crime acts as a barrier to participation in outdoor physical and social activities. Respondents with higher fear of crime levels *"exercised less, saw friends less often, and participated in fewer social activities compared with the less fearful participants"*.

The aforementioned studies clearly point out that fear of crime significantly affects human mobility behaviour. It affects the route choice of pedestrians, meaning pedestrians give up their habitual routes and adopt detours to avoid locations where they feel unsafe. Under more challenging circumstances, fear of crime forces people to switch from greener travel modes such as walking, cycling and public transportation, to using private vehicles. In the worst case scenarios, fear of crime restricts human mobility to such an extent that it disrupts their active social lifestyle, leading to physical and mental health problems.

2.3 EXISTING MITIGATION APPROACHES

Fear of crime in pedestrians has been proven to be detrimental for the society. Hence, researchers have been looking at ways to reduce fear of criminal victimisation while walking and improve safety perception of pedestrians in urban spaces. In this context, several studies have made significant contributions as they have proposed different types of solutions to tackle this problem. These methods have been classified into two broad classes.

2.3.1 *Improvements in urban design*

The first class of studies have investigated urban design or specific built environment attributes that influence crime, fear of crime and thus safety perception. These established the fact that people prefer certain built environment characteristics over others, with regards to safety. The general objective of these studies were not merely investigation about elements of urban design that affected fear of crime, but also highlighting these elements so that municipal authorities can be well-informed about necessary changes that can improve safety perception of pedestrians and reduce fear of crime. Given that the exposure of walking is significantly higher than any other mode of travel (lower speeds and lower levels of protection), these built environment characteristics influencing fear of crime, have the biggest impact on the mobility decisions of pedestrians.

Nasar (1983) assessed 60 residential scenes with a set of adjective descriptors of visual attributes and found that people preferred residential scenes which could be described as ornate, well kept, open and clear. Nasar (1990) conducted a study to uncover how public evaluates the cityscape with the help of a survey and consequently developed maps. These maps, also called the evaluative map of a city, suggested that people find naturalness and openness highly desirable. Sakip, Johari, and Salleh (2012) investigated the relationship between practices and attitudes of crime prevention through environmental design and the level of fear of crime in gated and non-gated residential areas. The study found that environmental design improvement improves the safety perception among people.

Yin (2013) developed an agent-based model to assess macro-level patterns of walkability across the city of Buffalo, New York, United States, using micro-level data. Here the model represented the interaction between pedestrians and their environment, and how that influences their walking behaviour. A range of physical and social environmental characteristics that were identified in the health and planning literature, including concerns for safety, as factors influencing walking behaviour, were used, such as presence of restaurants, grocery stores, parks, vacant land parcels and number of people using a place. Hong and Chen (2014) examined the relation between the built environment, perceived safety from crime and walking behaviour by conducting a travel survey in King County, Washington State, United States. They employed a two-stage least squares model and found that the built environment is significantly related to walking behaviour and also correlated with people's perception of safety. Choi, Seo, and Oh (2016) estimated the factors influencing walkability in the city of Busan, South Korea. The results suggested that perceived crime safety of pedestrians was greatly influenced by the presence of bars, night clubs and adult stores.

Blečić et al. (2016) conducted a regression analysis to find sidewalk width, architectural, urban and environmental attractions, density of shops, bars, services, economic activities, shelters and shades and street lighting as the factors influencing walkability and perceived safety. Traunmueller, Marshall, and Capra (2016) investigated the quantitative relationship between built environment characteristics and safety perception by using an online crowdsourcing approach. They used data on safety ratings given to images showing various combinations of built environment and people inhabiting it, by more than 500 users. The study identified what features of the urban environment increase or decrease the safety perception of people. These included the built environment, and the demographics of the people using them such as their age, gender and ethnicity. Rashid et al. (2017) found out that presence of hidden walkways, underground passageways, single land use, unkempt landscape, graffiti, litter and lack of lighting influenced the safety perception of pedestrians in Kuala Lumpur, Malaysia. Ferrer and Ruiz (2018) used a qualitative methodology to identify and compare built environmental factors that influence people's decision to walk for short trips, in two Spanish cities of Valencia and Granada. The study found that factors related to insecurity from crime, such as of absence of people, poor street lighting or walking along a conflictive area, were the main barriers to walking. Zhang and Mu (2019) used an assessment method for the objective measurement of walkability in the built environment by incorporating pedestrian preferences derived from a walking preference survey and developed a walkability rating system to determine the most walkable and unwalkable places in their study area. The factors considered in this study were presence of designated walking spaces, density of amenities and presence of bus stops.

Other studies presented significant relationships existing between built environment factors and crime occurrences. Salesses et al. (2013) used thousands of geo-tagged images of the cities of Boston, New York, Linz and Salzburg to measure the perception of safety among people, and found a significant correlation between perceptions of safety and the number of homicides. Halat et al. (2015) studied individual travel behaviour by applying discrete choice models to the reported home-based work trips in the Chicago household travel survey. Results suggested that both walk-score and crime index at the destination were significant predictors of mode choice of an individual. Values of the destination crime index coefficients indicated that destination zones with high crime rates discourage people from taking transit and walking, as compared to availing private vehicles. Adel, Salheen, and Mahmoud (2016) had identified elements of urban design that relate to crime occurrence within the Greater Cairo Region, Egypt, and proposed multiple approaches to reduce crime rates.

Zandieh et al. (2016) examined the inequalities in perceived built environment attributes and their possible influences on disparities in older adults' outdoor walking levels across Birmingham, United Kingdom, where they surveyed and collected movement data from 173 participants and correlated their findings with different attributes of the built environment. They identified that these attributes could be split into two categories. viz., macro attributes (e. g., residential density, land use-mix and route connectivity) and micro attributes (e. g., safety, pedestrian infrastructure and aesthetics). Drawing on the results of similar studies, others have proposed efficient methods of modification of these attributes, or have studied the impact of such modifications.

Fisher and Nasar (1992) examined fear of crime in relation to features on a college campus in Ohio, United States, by conducting a survey and observing pedestrian activity. Fear was found to be directly related to *prospect*, *refuge* and *escape* characteristics of outdoor places. Accordingly, they recommended changes in physical arrangement at the fear-generating places, increasing prospect and lowering refuge, to reduce fear of crime in outdoor walking environments. Painter (1994, 1996) evaluated the impact of a lighting improvement strategy in four crime-prone streets in London, United Kingdom, using attitudinal and behavioral measures. Results provided evidence that properly designed and focused street lighting improvements led to reductions in crime, disorder, and fear of crime. This was due to increased night-time usage which intensifies natural vigilance. Over 90% of pedestrians interviewed in the surrounding areas reported reduced fear of crime as a result of these lighting improvements.

Day et al. (2007) systematically evaluated the impacts of extensive renovation of built environment in a neighbourhood in California, United States, that was plagued by on-street crimes. This renovation included major changes in street furniture as well as changes in adjoining apartment buildings, surrounding sidewalks, and parking treatments. Respondents reported feeling more positive about their neighbourhood along with significantly greater walking activity after renovation. The authors suggested that the renovation may have contributed to the neighborhood's sustained reduction in violent crime, despite declining police presence. Colquhoun (2004) suggested a list of urban design improvements that could reduce crime and fear of crime. They proposed development of streets that promoted sociability, community and natural surveillance, and that had a lower speed limit for vehicles. They also proposed *permeable* neighbourhoods with adjoining shops and services, building height limitations and careful treatment of corners, vistas and landmarks.

2.3.2 *Location-based IT approaches*

The second class of studies propose IT approaches that are more inexpensive compared to the infrastructural overhauls. These include exploiting publicly available georeferenced social media data. These recent methods include developing novel pedestrian navigation tools that avoid or attempt to avoid possible unsafe locations, based on historical crime records or semantic analysis of tweets.

Fu, Lu, and Lu (2014) developed a travel route recommendation system, TREADS, that suggested safe travel itineraries in real-time by using *Twitter* data and *Yelp* reviews. The system retrieved transportation related tweets with high accuracy and applied a novel text-summarisation module on the tweets and reviews for safe route recommendation. Kim, Cha, and Sandholm (2014) proposed a navigation system, *SocRoutes*, based on the sentiments and perception of people about places obtained from geo-tagged tweets, to recommended safer, friendlier and more enjoyable routes to its users. SocRoutes recommends safer routes by avoiding places with extremely negative sentiments. Using data from Chicago, the authors validated that the recommended routes were marginally longer than the shortest available routes. They also claimed that from observed correlations, the recommended routes bypassed existing crime hotspots.

Mata et al. (2016) proposed a hybrid approach to recommend safe routes to users via a smartphone application. They integrated crowd-sensed Twitter data and official crime data, processed them semantically and classified them using Bayes algorithm. They tested their mobile information system using data from Mexico City. Vaghela and Shih (2018) proposed *WalkSafe*, a location-based smartphone application, designed for the campus safety of the college community of The Pennsylvania State University. WalkSafe notifies the user of the historical emergencies and incidents nearby, up to two days, based on the updates done to the University Police database. During user movement, the application is designed to notify the users in real-time if they are within the assigned threshold of locations with historic incidents and criminal activities, so that they can be aware and consequently avoid such locations and avail safer routes.

Furtado et al. (2012) proposed *WikiCrimes*, a website that uses a synthesis of crowd-mapping and crime-mapping with an aim to facilitate citizen crime prevention, provide more transparency and publicity to information on crime, and reduce the under-reporting of crime. Dewey (2014) describes a now-defunct application *SketchFactor*, where users could rate their perceived safety of an area and report acts of sketchy behavior, with the intention of empowering users to avoid harassment. Greenfield (2013) talks about another now-defunct application *Ghetto-Tracker*, later renamed *Good Part of Town*, that allowed users to rate the perception of safety of a particular area, with the intention of helping people avoid seemingly unsafe areas.

2.3.3 *Drawbacks of the existing approaches*

While these traditional approaches of reducing fear of crime among pedestrians are more established, they still suffer from a few major drawbacks. For studies that investigate urban design attributes that govern fear of crime in outdoor spaces, and recommend infrastructural modifications, the attributes mentioned can be classified into macro and micro attributes. The macro attributes e. g., alleyways, deserted areas, vacant land parcels, empty green-spaces, involve detailed planning efforts from the local councils and hence take significantly large time periods to be implemented. These changes are heavy on the budget, meaning they involve the expenditure of substantially large amounts of public money. Even if budget is not a challenge, it is not always possible to modify some of these macro attributes as they have utilities at hours of the day that are not critical. One such example is green spaces. While green spaces encourage feelings of vulnerability among pedestrians after dark, in urban areas, they are known to improve the physical and mental health of residents (Lim et al., 2018). Therefore, relocation or removal of green spaces, is challenging, but more importantly, unwanted. Even the modification of the micro attributes e. g., street lighting, alcoves, tall dense shrubs, blind spots, graffiti, involve significant time, effort and money. Hence, it is not always possible for the governing authorities and local urban councils to holistically address all such factors that discourage people from walking.

The second class of studies that rely on location-based IT approaches are relatively inexpensive. Yet they suffer from multiple drawbacks. First, crime is an outlier. Crime is an unusual event in space-time. On the other hand, fear of crime is more widespread than actual crime (Brown, Hirschfield, and Batey, 2000; Oc and Tiesdell, 1997). Fear of crime has a much greater influence on the safety perception of pedestrians than crime itself (Matei, Ball-Rokeach, and Qiu, 2001). Second, there are many such locations where people feel vulnerable, but such locations have no historical crime records. Given these methods are data-dependent, they are 'reactive' in nature, and hence suffer in the absence of appropriate data trying to represent fear of crime. Third, crime data and proxy social media data suffer from their own drawbacks when trying to represent fear of crime. They are not always correlated with fear of crime and run the risk of misrepresenting fearful places. Park et al. (2011) had stated that fear of crime and actual crime rates are substantially different from each other. Davis and Dossetor (2010) had stated that public perception of crime rates and the actual recorded crime rates across different countries do not match in most cases. Fourth, navigation decisions based on historical crime records and tweet sentiments indirectly create ghettos by isolating such areas even further. Systems with such approaches are prone to biases (over-representation of some demographics in contributing voluntary information), and therefore have the potential to profile certain racial and socio-economic groups (Wood, Ross, and Johns, 2021). This is detrimental for the overall walkability of the area, is less inclusive in nature, and hence, not desirable. For example, Dewey (2014) and Greenfield (2013) had stated how app-facilitated profiling became prominent in the cases of the now-defunct apps *SketchFactor* and *GhettoTracker/Good Part of Town* respectively. Both apps were taken down from the internet quickly after receiving online backlash.

2.4 WALKING ALONE AND FEAR OF CRIME

There is extensive literature that alludes to the relationship between fear of crime and *walking alone*. For example, Badger (2014) talks about fear of crime in women in her article in The Washington Post where the title is *"how women feel about walking alone at night in their own neighborhoods"*. Another prominent example is Roberts (2014), who discusses measurements of fear of crime in his article *"Fear of*

Walking Alone at Night". Sacco (1984) stated that people walking in their neighbourhood *alone* at night is considered to be a measure of adaptation to crime-related anxieties. This is supported by Roberts (2014) who mentioned that a common form of question that appears in many national crime surveys and also the European Social Survey is *"How safe do you feel or would you feel being alone in your neighbourhood after dark?"* He also mentioned that Gallup and the National Opinion Research Center (NORC) General Social Surveys (GSS) asks survey respondents the question *"Is there any area right around here – that is, within a mile – where you would be afraid to walk alone at night?"*

Clearly, these indicate that willingness to *walk alone* under critical circumstances is a widely accepted way of objectively measuring fear of crime. This means that although fear of crime is generated by a host of environmental cues that have been discussed in the literature, they mostly become prominent and influential when people are walking alone. In other words, factors that generate fear of crime only become critical when a person walks alone, without a companion, or without significant ambient pedestrian population. Hence, walking alone is an equally important factor, if not the most important one, as are the widely studied environmental cues that drive fear of crime while walking. The difference is that while these existing cues have been investigated widely, *walking alone* has never been investigated prominently as a critical factor that influences fear of crime.

Clifton and Livi (2005) studied safety perceptions of walking environments by analysing survey data from three Maryland communities with different walkability and socio-economic characteristics. Most of the female respondents stated that they felt much safer when they had a walking companion as compared to walking alone in seemingly fearful places. Other studies support this key finding. Ferrer, Ruiz, and Mars (2015) conducted a qualitative study to identify built environment factors that influence short distance walking trips. Half of the survey respondents stated that one of the main reasons for not walking for transportation was the absence of other people. Ferrer and Ruiz (2018) mentions the verbatim responses of a couple of these survey participants, where they explicitly mention that even in areas conducive for walking, they feel unsafe if there are less people around. This has been explained more explicitly in the following studies.

Iglesias, Greene, and Dios Ortúzar (2013) mentions that one of the three key attributes relating urban space to safety perception is *nat-*

ural vigilance. The presence of people, the distribution of points of observation (such as windows), and the movement of other pedestrians nearby, govern natural vigilance. In simpler terms, the more eyes there are on the street, the safer a person feels while walking alone. Painter (1994, 1996) assessed the impact of lighting improvements on crime and fear of crime along crime-prone streets in the United Kingdom. He stated that a major reason why street lighting improves safety is that more street lighting increases street usage. This means that the likelihood of the presence of capable guardians nearby increases, which not only improves safety perception, but improves actual safety as well. Cohen and Felson (1979) had stated that the proximity of other pedestrians deters offenders, as they run the risk of being recognised or get caught. All of these studies strongly suggest that walking with more people nearby is perceived as significantly safer than walking alone, especially under critical circumstances when people feel fearful. The presence of other pedestrians nearby boosts natural vigilance, thereby making pedestrians feel safer, thus improving perceived safety from crime. Also, the presence of other pedestrians nearby is not perceived as favourable by a potential offender, thereby improving actual safety from crime.

Despite the repeated acknowledgements of *walking alone* or *absence of other people nearby* in literature, studies have tried to address this issue passively. Studies such as Painter (1994) stated how improvement in street lighting can mean greater pedestrian activity. Colquhoun (2004) proposed neighbourhoods that have higher density of shops and services as a mean that can generate more ambient pedestrian traffic. Here, street lighting frequency or the density of shops and services act as proxy variables that govern the likelihood of ambient pedestrian footfall. However, there are a few considerations when it comes to such passive approaches that attempt to generate pedestrian traffic. These are highlighted as follows:

- Passive methods can be expensive, time-consuming and are subject to extensive planning before implementation.
- They are not easily transferable, meaning the same set of passive measures may not be appropriate for two different locations, especially if there exists cultural differences.
- Passive methods are not always guaranteed to work. For example, even under sufficient street lighting, residential areas may not exhibit sufficient pedestrian population at night. Another

example could be, that while density of amenities can generate footfall, they are usually not open after certain hours at night. When closed, such places of amenities are as good as absent.

In contrast to the aforementioned passive approaches, active vigilance approaches, or approaches that directly attempt to reduce walking alone, or walking without people nearby at critical times of the day, have only been used sparingly till now. Existing research has not rigorously investigated the application or effectiveness of active approaches to counter the challenge of reducing fear of crime or crime. Yet, there are a few programmes around the globe, that stand out in this regard.

The first one is Chicago's *Safe Passage Program*. Given Chicago's history of criminal activities, and based on evidence suggesting students are highly likely to experience violent crime while in transit to and from school, the Safe Passage Program was introduced by Chicago Public Schools (link to website). The Safe Passage program involves placement of local citizens to monitor designated routes for students traveling to and from school. The goal was to provide safe routes to and from school, and in doing so, theoretically reduce crime around schools. Chicago Public Schools estimated that their program led to a 20% decline in criminal incidents around "Safe Passage" schools, a 27% drop in incidents among students, and a 7% increase in attendance during its first two years (Sanfelice, 2019). Early evidence gathered by Curran (2018, 2019) suggested that there was a decrease of reported crime in the range of 5 to 17% along "Safe Passages" in comparison to streets two blocks away. Sanfelice (2019) assessed the effects of Chicago's Safe Passage program on local crimes. They also found that the intervention reduced crime along high school safe routes while in effect.

The second programme, and the one that is possibly more popular, is the *Safe Back Home Scouts* programme. *Safe Back Home Scouts* is a nighttime walking escort programme in Seoul, that was started in 2013 with a focus to increase pedestrian safety (Seoul Metropolitan Government, 2014). This involves two escorts accompanying a pedestrian to their home during off-peak after-dark hours (10 PM to 1 AM) (Baleun and Hwaya, 2019). This is directed towards assisting people who return home late at night and have fear of crime while doing so. To access this service, a person has to call a helpline operated by the city government, or put in a request via the city-run smartphone app *Ansimi*. The user is met by two scouts at a designated place and time, and the scouts escort the user to their destination (The Korea Times, 2013). Additionally, the scouts patrol crime hotpots and other areas such as ones near entertainment spots. They also report and respond to emergencies. As of October 2013, nearly 11,000 people had used this service in the preceding four months. By 2015, the scout had helped women reach home safely in more than 100,000 cases (Seoul Metropolitan Government, 2015). In 2016, Seoul Metropolitan Government launched a smartphone application *Get-Home-Safely Scout* for ease of requesting scout assistance on-the-go (Seoul Metropolitan Government, 2016).

Apart from these two programmes, universities have their own localised methods to address issues related to crime and fear of crime, on and around campus. One such program is having security escorts accompany a person across campuses of The University of Melbourne (University Security, The University of Melbourne). This service is freely available to all students and staff from anywhere on campus. One can book this service by calling university security.

While the aforementioned approaches attempt at actively boosting natural vigilance by reducing walking in absence of people nearby, and thereby bypasses the limitations of the passive methods discussed before, they too have their own drawbacks.

- Firstly, these approaches are localised. While these approaches can be adopted elsewhere, yet they remain sporadic. The major reason why these kind of programmes are not implemented across the globe is that they are government initiatives. Lack of standardisation, resources, and vision leads to such initiatives never being materialised.

- Secondly, these approaches are expensive. The *Safe Passage Program* in Chicago amounted to $17 million annually in 2015-2016 school year as it involves remunerating the monitors. The *Safe Back Home Scouts* programme also involves paying thousands of scouts who escort people safely to their destinations.

- Localised approaches may seem effective, but there is some evidence suggesting the improvement in safety is not straightforward. While Sanfelice (2019) suggested that the *Safe Passage Program* appeared economically worthwhile (considering costs of crimes reduced with cost of sustaining the programme), they also found geographical displacement of crimes. Although the

> nearest neighbours of designated streets experienced a drop in crimes, streets farther away experienced a slight increase in crimes due to this geographical displacement.

2.5 SHARED MOBILITY AND WALK-SHARING

The concept of walk-sharing is a potential new addition to the developing and rapidly growing universe of shared mobility. It is therefore reasonable to look into the literature related to shared mobility to understand the similarities and distinctions between walk-sharing and the existing forms of shared mobility.

2.5.1 *Ridesharing*

Social networks, location-based services, the Internet, and smartphones have all contributed to the growth of the sharing economy (sometimes referred to as peer-to-peer sharing, the mesh economy, and collaborative consumption). The sharing economy is a developing, yet widespread phenomenon in which goods and services are rented or borrowed rather than purchased. This sharing takes place between peers (e. g., community drivers, peer-to-peer carsharing, or bikesharing) or through businesses (e. g., a carsharing operator). The sharing economy has the potential to significantly increase efficiency, reduce costs, monetize underutilised resources, and provide social and environmental benefits.

One such aspect of the sharing economy is shared mobility, which is the shared use of a motor vehicle, bicycle, or other low-speed transportation modes. Rather than requiring ownership (sometimes for one class of participants), shared mobility allows users to obtain short-term access to transportation as needed. Santos (2018) stated that there currently exists multiple forms of shared mobility. Carsharing, personal vehicle sharing (i. e., peer-to-peer carsharing and fractional ownership), bikesharing, scooter sharing, ridesharing, and on-demand ride services are all examples of shared mobility forms.

Ridesharing (also known as carpooling) is one popular form of shared mobility where individual car-owners share a ride with another person with similar spatio-temporal trip characteristics (similar starting times, nearby origins and destinations). The difference between ridesharing and ridesourcing (also known as ride-hailing) is that the former is a semi-commercial setting (passengers share the cost of travel with the car owner), while the latter is a strictly commercial service (passengers pay the drivers via their online regulator for their service e. g., Uber, Lyft).

2.5.2 *Similarities between ridesharing and walk-sharing*

In this thesis, walk-sharing is presented as a social symbiosis devoid of financial incentives. Clearly, walk-sharing therefore becomes more similar to ridesharing, as opposed to ride-hailing. Ridesharing can also be a purely social endeavour, with no financial incentives. It can have mixed forms (non-commercial, but sharing benefits; personal financial settlements), such as neighbours swapping roles of driver/-passenger on a day-to-day basis; drivers picking up passengers on highway ramps to be allowed to use High-Occupancy Vehicle (HOV) lanes; etc. Although walk-sharing, similar to other shared forms of mobility, has the prospect to be converted into a commercial or semi-commercial service with a multi-sided market, exploring its economic and financial viability is not within the stated objectives of this thesis. The proposed walk-sharing scheme has structural similarities with ridesharing as follows:

- In walk-sharing, similar to ridesharing, individual travellers share their trip, or parts of it, with another individual with similar interests in terms of the origin, destination, trip time, or overlapping route segments of the trip being made.
- Walk-sharing and ridesharing are similar in various aspects such as matching people, pairing them up at a *meeting point* and detachment at a *separation point*.

Due to these fundamental similarities, the following sections present notable literature from the ridesharing domain. It is reasonable since there are possibilities of significant takeaways from such research that can be applied to walk-sharing research presented in the subsequent chapters of this thesis.

2.5.3 *The benefits of ridesharing*

Ridesharing participants benefit from shared travel costs, travel-time savings from high occupancy vehicle lanes, reduced commute stress, and often preferential parking and other incentives (Shaheen and Cohen, 2021; Shaheen, Cohen, Zohdy, et al., 2016). Furuhata et al. (2013) stated that ridesharing offers a set of direct benefits to the users, with a reduced cost of travel as compared to using a private vehicle alone or hiring a cab by themselves. Ridesharing means increased flexibility for the riders (non-car owners), and usually reduced travel times as compared to public transport. In other words, participants of ridesharing share their costs which leads to an increase in benefits. Apart from being beneficial to individual travellers, ridesharing has a host of community benefits, such as reduced traffic congestion, reduced demand for parking spaces, lower overall fuel consumption and reduced air pollution (Chan and Shaheen, 2012; Ferguson, 1997; Kelly, 2007; Morency, 2007).

2.5.4 *The costs of ridesharing*

In spite of these environmental and economic benefits, participation rates of ridesharing is still lower than expected (Amey, 2010). This is because of the fact that ridesharing, apart from being beneficial, has its own set of costs (deterring factors that make ridesharing inconvenient).

Ridesharing involves significant waiting times, i.e., the time period between requesting a ride and pick-up, which is an important performance measure of a ridesharing service (Guasch et al., 2014). Additionally, users are often required to travel a certain distance towards their designated optimum pick-up point. Furthermore, there are detour costs, which are required in ridesharing services to accommodate travel partners, which means travelling for longer distances and durations than availing the shortest possible routes when travelling directly to the destination (Wessels, 2009).

Apart from these spatio-temporal costs, there exists social costs when it comes to ridesharing. The aspect of trust on ridesharing companions is a pivotal factor for efficiency of ridesharing services. Sarriera et al. (2017) conducted a survey across the US to find that for ridesharing users, social interaction is a critical aspect, alongside time and cost. The perception of a negative social interaction during a shared ride acts as a deterrent in opting to choose ridesharing. Therefore, trust and feelings of perceived safety influence matching preferences, and consequently, the performance of ridesharing services.

2.5.5 *Modelling ridesharing*

Ridesharing has been studied extensively by researchers via modelling techniques. Nourinejad and Roorda (2016) presented a model for dynamic ridesharing wherein it was shown that when the system accommodates multi-passenger rides, it results in higher user cost savings and vehicle kilometres travelled savings. Fiedler et al. (2018) quantified the potential of ridesharing in a hypothetical mobility-on-demand system designed to serve all trips realized by private car in the city of Prague. They showed that by employing a ridesharing strategy, the travel time increases by no more than 10 minutes, the average occupancy of a vehicle increases to 2.7 passengers and the number of vehicle miles travelled decreases to 35%. Agatz et al. (2011) adopted an optimisation-based approach towards dynamic ridesharing that aimed at minimising the total system-wide vehicle miles incurred by system users, and their individual travel costs and that resulted in the improvement of performance of the ridesharing system as compared to simple greedy matching rules. Coltin and Veloso (2014) showed that by planning for transfers of passengers between multiple drivers, the availability and range of the rideshare service can be increased and reduce the total vehicular miles travelled by the network can be reduced as well.

Guasch et al. (2014) developed a simulation model to determine to most suitable type of dynamic ridesharing model given the limited numbers of responses received and the heterogeneous mobility patterns of drivers and riders in the community. Wang, Winter, and Ronald (2017) proposed a social network based ridesharing algorithm with heterogeneous detour tolerances for varied social contacts and studied from a theoretical perspective, matching rates and detour costs for different scenarios.

2.6 SUMMARY

This chapter has reviewed existing literature to provide a background for the study presented in this thesis. Existing studies were discussed to show that fear of crime is still a prominent issue in the urban context, despite rapid urbanisation and technological advancements. More focused studies were discussed which showed that fear of crime negatively affected human mobility decisions, especially those related to walking. This strengthened the argument that fear of crime is the biggest deterrent for walking when a walking trip is convenient otherwise. Thereafter, studies that proposed different interventions to reduce fear of crime and improve pedestrian safety and safety perception, were presented.

Consequently, it was argued on the basis of statements and findings from multiple studies that *walking alone* is the major catalyst for pedestrians feeling fearful outdoors. Existing studies that proposed approaches to boost natural vigilance so that pedestrians feel safer, were classified into two categories viz., passive and active. While the drawbacks of passive approaches were more prominent than the active ones, the existing active vigilance approaches are fewer in number, have localised safety effects and are expensive. It is apparent that there exists the need for a smarter approach to improve natural vigilance for pedestrians based on the current state-of-the-art location-based services, that can surpass the drawbacks of not only the passive approaches, but also the shortcomings of the active vigilance strategies.

Along these lines, this thesis introduces walk-sharing, a smarter way to improve the uptake of walking in the urban mode share. By matching people with similar spatio-temporal interests who are willing to walk to their respective destinations, walk-sharing actively improves natural vigilance by ensuring companionship for pedestrians for a part or the entirety of their journey. As the presence of a companion boosts natural vigilance, thereby deterring potential offenders from committing crimes, walk-sharing not only improves the safety perception with regards to walking, but it promises to improve actual safety of pedestrians as well. Walk-sharing is a proactive and inexpensive intervention that can be up-scaled and transferred without major design modifications. Unlike its existing counterparts, walk-sharing is independent of historical crime data, proxy crime data, or any other data that attempts to represent fear of crime in outdoor spaces, does not require expensive infrastructural overhauls, can be applied anywhere, and can be easily accessed by the community given the abundance of smartphones.

By reducing fear of crime while walking, walk-sharing has the potential to make walking more attractive, thereby improving its modal share for short-distance trips, and consequently, reduce motorised traffic, thereby reducing emissions and congestion. Also, by increasing the amount of walking in the daily routines of people, walk-sharing promises to improve their physical and mental well-being, thereby boosting public health in the long run. Finally, ridesharing literature was discussed due to the structural resemblance between ridesharing and the proposed novel walk-sharing scheme.

Walk-sharing has been introduced as an intervention to reduce fear of crime while walking, thereby improving the safety perception of people around walking, thus making walking a more attractive proposition, especially when it is convenient otherwise. It was discussed in Section 2.1 how fear of crime is a major challenge in the urban context, one that has significant negative impacts on the uptake of walking. Fear of crime causes psychological issues such as anxiety and paranoia on a personal level. Arguably, the psychological impacts of fear of crime is more widespread than actual crime (Matei, Ball-Rokeach, and Qiu, 2001; Ruijsbroek et al., 2015). Section 2.3 had discussed how existing methods that work with crime occurrence data run the risk of misrepresenting fear of crime. Davis and Dossetor (2010) had shown that the disparity between perceived crime rates and actual crime rates was prevalent across different countries. Unlike existing methods, walk-sharing aims to address the more widespread fear of crime that negatively impacts active mobility modal share. Furthermore, it was discussed in Section 2.4 that walking alone, or walking without significant natural vigilance, is the primary reason for feeling fearful in outdoor environments. As people walk together (as proposed by walk-sharing), they walk alone less or do not walk alone at all, consequently reducing their feelings of fear of crime outdoors (Clifton and Livi, 2005). Therefore walk-sharing, which introduces the concept of ad hoc matchmaking and companionship for walking for transport, in principle should prove effective at improving safety perception about and while walking.

However, walk-sharing is not only limited to reducing fear of crime. Walk-sharing could significantly impact the rates of actual on-street crime as well. In Section 2.4, it was discussed that natural vigilance, or the presence of capable guardians nearby, improves not only perceived safety, but also actual safety, as potential offenders feel more vulnerable since chances of being overpowered, being recognised or getting caught increases significantly (Cohen and Felson, 1979). Significant results of safety improvements were obtained in a similar active vigilance approach, Chicago's *Safe Passage Program*, where reported crime occurrences nearby dropped up to 17%. Walk-sharing, being a smarter active vigilance approach, could have similar impacts in terms of drop in actual crime rate, if not more. In simpler terms, walk-sharing may not only improve the perception of people with regards to safety in walking, but also it can improve actual safety from crime.

Based on the extensive literature reviewed in this chapter, the following research gaps have been identified:

- Existing passive approaches that aim to reduce fear of crime are expensive, time-consuming and are subject to extensive planning before implementation. Other relatively low-cost passive approaches are not easily transferable, and are not foolproof. Existing active vigilance approaches involve human effort, are costlier, and challenging to sustain. Hence, there is need for a low-cost active approach, which is scaleable and transferable, to tackle fear of crime among pedestrians.
- As walk-sharing is introduced for the first time in scholarship, there is a need to establish its fundamentals, viz., conceptual model, costs and critical factors.
- To gauge the abilities of walk-sharing in terms of pedestrian safety improvement, it is necessary to measure its performance objectively and test for its technical viability. Hence, detailed modelling of the walk-sharing system is necessary along with simulation under multiple plausible scenarios.
- Given the novelty of walk-sharing, it is also unknown how the community, consisting of potential users of walk-sharing, perceives walk-sharing and what their preferences are. A detailed understanding of community feedback is needed to gain deeper insights into the acceptability of walk-sharing.

- The practical viability of walk-sharing is also unknown. This needs to derived by investigating spatio-temporal and social thresholds of the people in the community.

These research gaps are addressed in the subsequent chapters of this thesis.

3

FUNDAMENTALS OF WALK-SHARING

*This chapter is based on the manuscript "***Exploring the viability of walk-sharing in outdoor urban spaces***" published in* Computers, Environment and Urban Systems *by Bhowmick, Winter, Stevenson and Vortisch (2021). My contribution as the first author of this manuscript includes proposing the hypothesis and the research problem, designing a systematic literature review method, design and implementation of research methods, analysing the results and presenting the discussion and conclusions. These works were supervised by Prof. Stephan Winter (my primary supervisor at The University of Melbourne), Prof. Mark Stevenson (my co-supervisor at The University of Melbourne), and Prof. Peter Vortisch (my primary supervisor at Karlsruhe Institute of Technology) who provided feedback and suggestions at every stage of this study.*

This chapter of the thesis discusses in detail the fundamentals of the proposed novel walk-sharing scheme. First, it describes what walk-sharing is, and how it aims to combat the challenge of improving safety and safety perception of pedestrians. It then presents the major contrast in concepts between walk-sharing and ridesharing. Later, it presents a simple technical framework of walk-sharing in space, and then presents an abstraction of the proposed walk-sharing system in the form of a conceptual model. Finally, the costs of walk-sharing and the factors that are critical to the viability of walk-sharing, are identified and defined.

3.1 INTRODUCTION

Walk-sharing is a novel, smarter intervention proposed to reduce fear of crime among pedestrians, improve their safety and safety perception, and thereby increase the uptake of walking for transport. Walk-sharing attempts to actively address the challenge of pedestrians feeling fearful of criminal victimisation in the absence of a walking companion, or other pedestrians nearby. Walk-sharing exploits the spatio-temporal overlap of people's location and their trip details (starting time, destination, route) to match them, so that they can walk together instead of walking alone. By ensuring a companion during a part or the entirety of their walking trips, walk-sharing attempts to minimise walking alone under critical circumstances. As the presence of a walking companion is known to make people feel safer and reduce the likelihood of crime while walking, walk-sharing makes walking more attractive to people. More walking would mean increased amounts of physical and mental health benefits, especially for people who would have avoided walking under the influence of fear. Also, as people walk more, the demand for other forms of transport, mostly motorised modes, goes down, especially for short trips that are convenient for walking. This would mean fewer unnecessary motorised trips, leading to less fuel consumption, less emissions and more sustainable urban living.

3.2 RESEARCH QUESTIONS

This chapter aims to answer the following research questions.

1. How can a walk-sharing system be designed?
2. While the benefits of walk-sharing are apparent, what are the possible deterrents (costs) of walk-sharing?
3. What are the factors that will be critical to the performance of walk-sharing?

3.3 ADVANTAGES OF WALK-SHARING

Walk-sharing is a smarter approach to reduce fear of crime in relation to walking in outdoor spaces. It overcomes the drawbacks of the existing approaches that aim to reduce fear of crime, but are usually expensive, time and effort intensive, localised, or inexpensive but dependent on data that is inappropriate at representing seemingly unsafe places.

Walk-sharing is relatively *inexpensive, scaleable and transferable*. Traditional approaches that involve urban design overhauls, or improvement and installation of street-related furniture are expensive. They involve significant amounts of time and human effort. In comparison, the financial cost of implementing a walk-sharing system is minuscule, especially given the fact that this system, once developed, could be upscaled and implemented anywhere.

Walk-sharing is a *proactive* approach of improving the safety of pedestrians. Unlike the more recent, smart approaches that exploit location-based services, walk-sharing is independent of any data. Existing approaches that try to identify seemingly fearful outdoor places using proxy historical crime or social media data are reactive approaches, sensitive to datasets not appropriate at representing fear of crime. Given the subjective nature of fear in people, it is extremely challenging to identify universally fearful places, or places that even a small portion of people would be afraid of while walking. Walk-sharing, in comparison, does not depend on identification of fearful places at all. It presents itself to a potential user in their time of need. This means if even a few people feel fear of crime at a place or at places along a route, which are not universally identified as places generating sense of fear, they can avail walk-sharing. Therefore, walk-sharing overcomes the challenge of subjectivity of fearfulness in people, by not having the necessity to objectively identifying fearful places.

Walk-sharing is a *smarter* approach. Given the popularity of smartphones and location-based services that go along with it, and the growing market for shared mobility platforms, walk-sharing has the potential to be widely implemented and easily accessed by everyone. Walk-sharing is not an expensive intervention, but still promises to improve safety and safety perception of pedestrians significantly. The subsequent chapters of this thesis have discussed methods that quntifies the impact of walk-sharing in this regard.

3.4 COMPARISONS WITH RIDESHARING

Section 2.5 discussed how walk-sharing could be a new addition to the host of shared forms of mobility existing currently. Among those, ridesharing, a semi-commercial service, where car-owners share a trip with a passenger having similar spatio-temporal interests, in exchange for sharing of fuel and other related expenses, was found to be most similar to the proposed walk-sharing scheme. Walk-sharing has some structural similarities with ridesharing, as was discussed in Section 2.5. Like ridesharing, in walk-sharing, individual travellers share their trip, or parts of it, with another individual with similar interests in terms of the origin, destination, or overlapping route segments of the trip being made. Walk-sharing and ridesharing are similar in various aspects such as matching people, pairing them up at a *meeting point*, sharing a substantial portion of their trip, and finally detachment at a *separation point*.

Figure 2 shows a simple technical framework of the proposed walk-sharing scheme in space. P_i and P_j are two pedestrians wanting to avail walk-sharing. After getting matched with each other, they leave from their respective origins (O_i and O_j) and walk to their advised meeting point (MP_{ij}). Consequently, they walk together and thus share their walk till their advised separation point (SP_{ij}). From the separation point, they walk alone towards their respective destinations (D_i and D_j). It must be noted that the scope of this thesis is limited to pairwise walk-sharing only. This means that in any single walk-share, the maximum number of participants is restricted to two people.

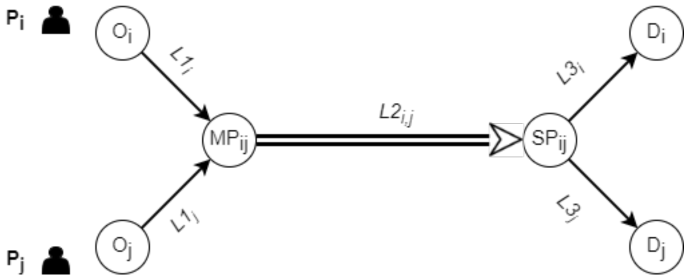

Figure 2: Schematic framework of walk-sharing

The major distinction between the widely popular ridesharing service and the proposed walk-sharing scheme is the mode of travel. While ridesharing involves motorised vehicles, walk-sharing is limited to pedestrian journeys. There are other fundamental differences that are noteworthy as well. These are discussed as follows:

- As walk-sharing is meant for pedestrian journeys, walk-sharing trips will be shorter in length on average than ridesharing trips.
- Ridesharing offers a set of direct benefits to the users, with a reduced cost of travel as compared to using a private vehicle alone or hiring a cab by themselves, and increased flexibility and often reduced travel time as compared to public transport (Furuhata et al., 2013). On the contrary, walk-sharing does not offer apparent financial benefits. While it may save money spent on alternative motorised travel mode, but walk-sharing is primarily intended to encourage travel on foot even at critical times

of the day when the user could feel vulnerable in certain outdoor spaces, and otherwise would opt for alternative (possibly motorised) means of transport.

- In ridesharing, there are two types of people involved, the car-owners/drivers and the passengers. In principle, ridesharing platforms are multi-sided platforms (Navidi, Nagel, and Winter, 2019), serving a two-sided market. But, the intention here is to present walk-sharing (at least initially) as more of a social symbiosis devoid of monetary incentives, than anything else. It does not involve one party that only walks to serve the interests or needs of another party. Hence, two people who bear similar interests, given their spatio-temporal proximity, may share a walk with each other. Hence, more people willing to walk-share nearby will make the walk-sharing service more attractive for another person willing to walk-share. Thus walk-sharing will feed from "*same-side exchange benefits (benefits derived by interaction among members of a single class of participant)*" (Gallaugher, 2015). In principle, potential pedestrians are the demand as well as the supply, and thus walk-sharing can be similar to a one-sided market, although there remains the scope to convert it into a multi-sided market. However, that is not included in the scope of this thesis.

3.5 CONCEPTUAL MODEL OF WALK-SHARING

Based on the simplistic technical framework of walk-sharing described in Section 3.4, a more detailed conceptual model was developed. While Figure 2 illustrates how walk-sharing would work across space, it ignores the aspect of the matchmaking process that occurs before. The conceptual model, illustrated using Figure 3, fills up this void.

A pedestrian enters the system of walk-sharing if they are willing to participate in it. It is assumed that the request put forward by the pedestrian to participate in walk-sharing happens impromptu. They are unable to set an intended start time for their trip beforehand. Hence, as soon as the pedestrian enters the walk-sharing system, they are absorbed in the matching pool. The matching pool consists of other pedestrians who are also willing to participate in walk-sharing. Consequently, the system constructs a distance matrix at that time step, with each element of that matrix representing the spatial and social impedance between each pair of pedestrians. The pedestrians are then matched in a pairwise manner using a heuristic matching process.

Once a pair of pedestrians are matched to each other, the system computes a meeting and a separation point based on their respective origins and destinations. These matched pedestrians are then discarded from the matching pool, and they start walking towards their designated meeting point, thereby starting the walk-sharing process, as illustrated in Figure 2. The matching process is not exhaustive, meaning that based on some spatial impedance cutoff and the matchmaking heuristic, some pedestrians are left unmatched. The system checks whether these unmatched pedestrians have not used up their maximum preferred waiting time. If they have residual waiting times, they remain in the matching pool, and this matching pool moves forward in time to be replenished by new pedestrians willing to participate in walk-sharing. Pedestrians, who do not have any more residual waiting time, give up on walk-sharing, leave the matching pool and the system, and travel alone to their destination.

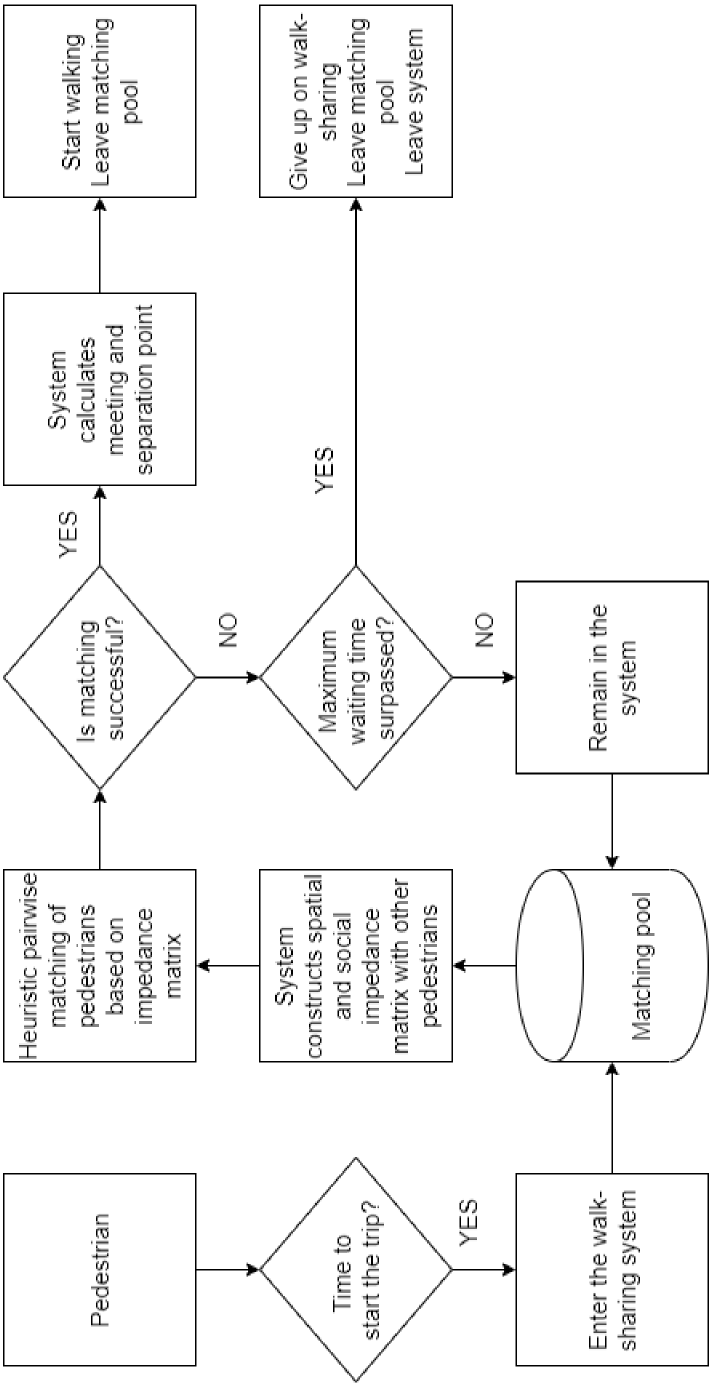

Figure 3: Conceptual model of the proposed walk-sharing system

3.6 THE COSTS AND PERFORMANCE METRICS OF WALK-SHARING

While the proposed walk-sharing scheme is seemingly beneficial in terms of improving an individual's perception of safety in seemingly unsafe walking environments, and thereby improving the appeal of walking, there are certain aspects of walk-sharing that could act as deterrents. These are referred to as the *costs*. Discussing these costs is an integral part of this study. Apart from identification of these costs, it is also essential to define them objectively for the purpose of measuring the performance of the proposed walk-sharing system. In principle, the lower the magnitude of costs, the greater is the efficiency of walk-sharing. Since both ridesharing and walk-sharing share the fundamental mechanism of matching and pairing people together, some of the identified costs of walk-sharing are similar to those involved in ridesharing. The identified costs that are relevant to walk-sharing are discussed below in detail.

- **Waiting time**: A critical factor that drives the efficiency of ridesharing services is *waiting time* (Guasch et al., 2014; Huang et al., 2014) where people wait for their rides to pick them up after getting matched. The concept of waiting time is also transferable to walk-sharing as participants are subjected to matchmaking based on each other's spatio-temporal placements. Therefore, walk-sharing participants may have to wait before being matched with an appropriate companion. In walk-sharing, waiting time is defined by the time difference between a willing participant becoming active in the system at the time in which they want to start their walking journey, thereby putting through a request, and the system returning a successful match. This is shown using Equation 1. Greater waiting times mean that the utility of the walking trips reduce. Hence, waiting time is a cost that needs to be minimised to improve the efficiency of walk-sharing.

  $$WaitingTime_{P_i} = T_{matched,P_i} - T_{start,P_i} \tag{1}$$

  Here P_i is a pedestrian who wishes to avail walk-sharing, T_{start,P_i} is the time when the pedestrian becomes active on the system and makes a request for walk-sharing (coincides with the earliest time at which the pedestrian wishes to start their journey) and $T_{matched,P_i}$ is the time when the pedestrian is matched with a suitable companion. It must be noted that a prior request (requesting a start time in future, and getting matched before one's original start time) is beyond the scope of the proposed walk-sharing framework.

- **Walk alone length**: *Walk alone length* is the length that a pedestrian availing walk-sharing has to walk alone without any companion, and comprises of two walking lengths, one between the origin and the meeting point and the other between the separation point and the destination. Since the objective of walk-sharing is to reduce the sense of fear by making people walk together instead of walking alone, walk alone length is a component that clearly needs to be minimised to fulfill the primary objective of walk-sharing. Large walk alone lengths would render walk-sharing ineffective as an intervention trying to reduce fear of crime among pedestrians.

  $$\begin{aligned} WalkAloneLength_{P_i} &= L_{origin,meeting\_point} \\ &\quad + L_{separation\_point,destination} \\ &= L1 + L3 \end{aligned} \tag{2}$$

  $L_{a,b}$ indicates length of shortest path between a and b.

- **Detour length**: Another major factor that determines the popularity of ridesharing services is the *length of detours* (Wang, Winter, and Ronald, 2017). Detours are a result of accommodating for the different origin-destination locations of the travel companion and yet find an optimal route. Likewise, in walk-sharing, when two pedestrians are paired up with each other, and they do not share the same origin and destination, a detour is likely. Thus, detour length is defined as the difference between route length while availing walk-sharing and shortest route length if the person would have walked alone to their destination (as shown in Equation 3 and Equation 4). Increased detours will reduce the attractiveness of walk-sharing scheme in the community given that walking detours take up much more effort and time than detours on motorised modes.

$$\begin{aligned} WalkSharingRouteLength_{P_i} &= WalkAloneLength_{P_i} \\ &\quad + L_{meeting\_point,separation\_point} \\ &= WalkAloneLength_{P_i} + L2 \end{aligned} \tag{3}$$

$$\begin{aligned} \mathsf{DetourLength}_{P_i} &= \mathsf{WalkSharingRouteLength}_{P_i} \\ &\quad - L_{\mathsf{origin,destination}} \\ &= \mathsf{WalkSharingRouteLength}_{P_i} - L4 \end{aligned} \tag{4}$$

- **Matching rate**: *Matching rate* (although not a 'cost') is one of the most critical performance metrics of ridesharing services (Agatz et al., 2011; Bozdog et al., 2018; Nourinejad and Roorda, 2016; Wang, Winter, and Ronald, 2017). Similar to ridesharing, in walk-sharing, matching rate is expressed as the percentage of the population willing to participate in walk-sharing, that is matched with a spatio-temporally preferable companion. A higher matching rate is essential to ensure success of the proposed walk-sharing scheme.

3.7 FACTORS CRITICAL TO THE VIABILITY OF WALK-SHARING

It is also necessary to understand how the costs of walk-sharing varies, and under which circumstances can they be minimised. Hence, the next step in this study needs to investigate on factors that could significantly govern these costs, and thereby, are critical to the performance of walk-sharing. This would form the prerequisite to deriving the nature of the relationships between these costs and critical factors, and consequently, investigating the viability of walk-sharing. The performance of the proposed walk-sharing scheme is expected to be influenced by the following factors:

- **Pedestrian demand**: *Pedestrian demand* indicates the number of people present in the system willing to participate in walk-sharing, in a given neighbourhood in a given time interval. It is expected that the more people there are in such a local system (in a common neighbourhood) searching for companions (higher pedestrian demand), the more likely it is to have more acceptable levels of performance metrics. More demand means more people nearby which means higher chances of getting matched, lesser walk alone lengths and lesser waiting times. This also means that in a real-world scenario, where pedestrian demand varies by the time of the day, performance of the walk-sharing scheme will depend on the time of the day as well.

- **Distance to buddy threshold**: *Distance to buddy* is a measure of the spatial separation between two potential walking companions (buddies). *Distance to buddy* has two components, *(a)* distance between the respective origins of two potential companions and *(b)* distance between the respective destinations of two potential companions. Thus *distance to buddy* not only measures the spatial separation between two origins, but takes into account the spatial separation between two respective destinations as well. For example, two pedestrians, having origins in proximity, may have spatially far enough destinations that walk-sharing will be impractical.

$$\mathrm{DistanceToBuddy}_{P_i,P_j} = \sqrt{\begin{aligned}&\mathit{dist}(\mathrm{origin}_i, \mathrm{origin}_j)^2 \\ &+ \mathit{dist}(\mathrm{destination}_i, \mathrm{destination}_j)^2\end{aligned}} \tag{5}$$

Here P_i and P_j are two potential walking companions. Given a *distance to buddy* threshold, the match is only possible if $\mathrm{DistanceToBuddy}_{P_i,P_j}$ is less than or equal to the preferred threshold (D_{th}).

$$\mathrm{DistanceToBuddy}_{P_i,P_j} \leqslant D_{th} \tag{6}$$

In principle, the higher the threshold is set, the greater chances for a pedestrian to get a match. Waiting times may reduce, but it will be more likely that detours and walk alone lengths get longer.

It must be noted that Equation 5 uses a sum of squares of the distances ($\sqrt{d_1^2 + d_2^2}$) instead of a linear addition ($d_1 + d_2$). This means that when the absolute difference between d_1 and d_2 is maximum (i. e., either $d_1 = 0$ or $d_2 = 0$) for a constant value of $d_1 + d_2$, *distance to buddy* is maximum for the given pair of distances. On the other hand, when the absolute difference between d_1 and d_2 is minimum (i. e., $d_1 = d_2$) for a constant value of $d_1 + d_2$, *distance to buddy* is minimum for the given pair of distances. This is unlike a linear addition, where a constant sum of d_1 and d_2 would result in the same value every time ($1 + 4 = 5$, also $2 + 3 = 5$). This non-linear addition penalises unequal magnitudes of origin distance $\mathit{dist}(\mathrm{origin}_i, \mathrm{origin}_j)^2$ and destination distance $\mathit{dist}(\mathrm{destination}_i, \mathrm{destination}_j)^2$.

In the matching algorithms showed in Chapter 3, this can separate *distance to buddy* values, when the sum of their origin and destination distance are the same. An even distribution of *distance to buddy* over two legs, (1) from origin and (2) to destination, would result in the walk alone length evenly distributed over these two legs as well. Walking is much more convenient and likely over shorter trip lengths as compared to longer ones. 63% of trips under 1 kilometre are walked, while that proportion goes down to 31% and 13% for trips between 1 and 2 kilometres and 2 and 3 kilometres respectively (Eady and Burtt, 2019). Similarly, two shorter walk alone legs are more preferable than one longer walk alone leg, as the perception of risk would vary non-linearly, and therefore greater continuous walk alone lengths would seem more unsafe. Hence, Equation 5 promotes equally distributed legs over unequal ones.

- **Distance to destination threshold**: Walking trips usually are of typically shorter lengths as compared to other modes of transport. But they often are longer as suggested by the average walking trip distances (around 1000 m) observed in the literature (Arasan, Rengaraju, and Rao, 1994; *Pedestrian Access Strategy : A strategy to increase walking for transport in Victoria* 2010; Rahul and Verma, 2014; Robertson, Thoreau, and Allsop, 2004; Yang and Diez-Roux, 2012). The distance between the origin and the destination, in principle, will affect the performance of the proposed walk-sharing scheme. For example, people walking for longer distances may find it hard to get matched to suitable companions if demand is low. If matched, detour length could be high. Hence, if destinations are farther away, matching rates will go down due to the diminishing number of suitable companions, waiting times and detours should increase substantially.

$$\mathrm{DistanceToDestination}_{P_i} = \mathit{dist}(\mathrm{origin}_i, \mathrm{destination}_i) \quad (7)$$

- **Maximum waiting time**: As discussed in Section 3.6, waiting time will be a critical factor that drives the efficiency of the proposed walk-sharing scheme. As waiting time is a cost of walk-sharing, it is highly likely that people availing walk-sharing will have preferences with regards to the maximum time they are willing to wait before they start looking for alternative travel choices. This is referred to as *maximum waiting time*.

$$WaitingTime_{P_i} \leqslant WT_{max,P_i} \quad (8)$$

> So, if a person does not receive a suitable match before their preferred waiting time WT_{max,P_i}, it is highly likely that they will give up, which will negatively affect the performance metrics. People willing to wait longer are more likely to get suitable matches.

These factors have been selected for their significant impact on the performance of walk-sharing. However, this thesis makes no such claims that these are the only factors that could be critical to walk-sharing. There could be additional factors such as (but not limited to) demographic thresholds, companion preferences, trust thresholds, land-use, urban form and network morphology. But in this study, the aim is to test the technical or theoretical viability of walk-sharing and the four factors discussed in detail are critical in this regard. Relationship between the factors beyond the scope of this study will be established in future studies as these are more complex and can only be accurately judged with more information.

3.8 DISCUSSION

One of the objectives of this chapter was to present the design of the proposed hypothetical walk-sharing system. In that regard, comparisons with shared mobility forms, mainly ridesharing, were outlined in the beginning. The reason behind this was to exploit the structural characteristics shared by walk-sharing and ridesharing, implementing them while developing the technical framework (shown in Figure 2) and eventually the conceptual model (shown in Figure 3).

The conceptual model was an abstract representation of how a walk-sharing system could be designed. It would eventually serve as the skeleton for the more sophisticated agent-based walk-sharing simulation model in the subsequent chapters. The conceptual model derives its logical foundations from the vast array of literature on shared forms of mobility. This was a result of the apparent similarities between these existing forms and walk-sharing cited in Section 2.5. The presented model is quite simplistic in nature. Yet, the model accommodates ad hoc matchmaking between participants interested in walk-sharing. The system can react based on any form of demand fed in to it, and does not require prior knowledge of the spatio-temporal preferences of the participants. On the flip side, the model does not allow people to book walks in advance, i. e., prior to them entering the system and consequently, the matching pool. The model only allows participants to enter the system, when they ideally wish to start their journey. If they are matched in the first iteration, waiting time is minimum. However, that can increase, depending on the circumstances.

As was discussed in Section 3.4, this thesis introduces walk-sharing, and therefore, walk-sharing is presented as a form social symbiosis between people. Participants in walk-sharing are considered, for the rest of this thesis, as having no financial interests. All participants, therefore, are considered to hail from the same class. Hence, the proposed conceptual model does not include the possibilities of financial costs and benefits between the participants, as is common in other forms of mobility.

The other objectives of this chapter were to understand the costs of walk-sharing and the critical factors influencing its performance. It was apparent that the outlined costs and critical factors are spatio-temporal in nature. Although reluctance to encounter unpleasant social interactions have been cited as an obstacle to ridesharing (Sarriera et al., 2017), the more significant factors influencing ridesharing participation are spatio-temporal in nature (Agatz et al., 2011; Coltin and Veloso, 2014; Fiedler et al., 2018; Guasch et al., 2014; Nourinejad and Roorda, 2016; Wessels, 2009). Similarly, costs and critical factors that are spatio-temporal in nature, are more relevant as a first filter to check for the viability of walk-sharing. Also, the influence of social factors on the participation numbers are difficult to gauge without on-ground implementation of a service, especially when walk-sharing, at this time, is only at an rudimentary stage of research. Although Chapter 5 discusses the community preferences on walk-sharing, the influence of socio-demographic characteristics on the likelihood of participation in walk-sharing will still be challenging to decipher. Hence, the scope of this thesis includes only the costs and critical factors as outlined in this chapter.

This was also an opportunity to discuss the differences between walk-sharing and ridesharing, thereby making the case for investigating the viability and effectiveness of walk-sharing independently. In contrast to ridesharing, where the cost of travel is shared among the car-owner and the passenger(s), the objective of walk-sharing is different. Walk-sharing aims to improve safety perception of pedestrians by making them walk together, matching them in terms of their spatio-temporal proximity via a common platform. Also, the participants in walk-sharing hail from a single class, meaning their objectives are the same, and they mutually benefit from participating in walk-sharing. Although, it must be noted that, while at this moment, walk-sharing has been presented as a social symbiosis devoid of commercial angles, it has the potential to be expanded into a semi-commercial (reward points from commercial sponsors) or commercial platform. This means people get incentives from sponsors in the form of rewards, e. g., supermarket discounts and brand gift cards. This could also generate volunteers participating in walk-sharing who gain such financial benefits from escorting pedestrians to their destinations who are in need of walking companionship, making it a heterogeneous market.

3.9 CONCLUSIONS

With pedestrians feeling vulnerable outdoors at critical times of the day, the appeal of outdoor walking has gone down significantly, resulting in people switching to costlier alternatives, or not walking at all. While safety improvement of pedestrians is looked into by the local urban councils, infrastructural overhauls involve large financial expenses, and significant completion times. This chapter proposed walk-sharing, a novel, proactive and cost-effective intervention to improve safety perception of pedestrians and reduce fear of crime. Walk-sharing involves matching potential pedestrians in spatio-temporal proximity and making them walk together. This way, pedestrians can overcome their fear of victimisation from crime by not walking alone, and also not look for costlier alternatives to reach their destination. In principle, walk-sharing can be beneficial to the community as it improves safety perception of pedestrians, improves pedestrian safety outdoors, increases pedestrian traffic, reduces motorised traffic and thus increase liveability of urban areas.

This chapter discussed how walk-sharing aims to reduce fear of crime by making people walk together in companionship. Then, a simple technical working framework for walk-sharing in space was explained, followed by the differences in fundamentals between walk-sharing and the widely popular ridesharing service, thereby arguing the necessity to pursue with the independent investigation about the viability of walk-sharing. Later, a conceptual model of walk-sharing was illustrated and explained. This was intended at projecting an abstract idea of how the mechanism of walk-sharing could work in the real-world. Finally, the costs of walk-sharing and the factors critical for driving these costs were explained. Costs included *waiting time*, *walk alone length*, *detour length* and *matching rate*. These costs will be used as objective measures of walk-sharing when testing for its viability. The critical spatio-temporal factors identified were *pedestrian demand*, *distance to buddy threshold*, *distance to destination threshold* and *maximum waiting time threshold*. Variation in levels of these factors will be used to analyse how the identified costs vary against them. This will be essential for determining the viability of walk-sharing subsequently.

In the following chapter, the conceptual model of walk-sharing is materialised into an agent-based model to run simulations and thereby measure its performance objectively. By conducting sensitivity analysis under theoretical scenarios, the logical efficacy of the developed model is checked. Additionally, it tests for the technical viability of walk-sharing in a real-world data-driven urban scenario.

4

EXPLORING THE TECHNICAL VIABILITY OF WALK-SHARING

*This chapter is based on the manuscript "**Exploring the viability of walk-sharing in outdoor urban spaces**" published in* Computers, Environment and Urban Systems *by Bhowmick, Winter, Stevenson and Vortisch (2021). My contribution as the first author of this manuscript includes proposing the hypothesis and the research problem, designing a systematic literature review method, design and implementation of research methods, analysing the results and presenting the discussion and conclusions. These works were supervised by Prof. Stephan Winter (my primary supervisor at The University of Melbourne), Prof. Mark Stevenson (my co-supervisor at The University of Melbourne), and Prof. Peter Vortisch (my primary supervisor at Karlsruhe Institute of Technology) who provided feedback and suggestions at every stage of this study.*

This chapter of the thesis builds on the theoretical foundations discussed in Chapter 3 and aims to test the technical viability of walk-sharing. It involves the proposal of algorithms to realise the conceptual model presented in the previous chapter, and convert it into an agent-based simulation model. This helps in the measurement of performance of walk-sharing, but also helps establish *proof of concept* by running simulations using multiple parameter settings to derive the nature of relationship between the identified costs and the critical factors. The chapter concludes by testing the performance of walk-sharing and therefore, its technical viability, by using real human mobility data.

4.1 RESEARCH QUESTIONS

This chapter aims to answer the following research questions.

1. How sensitive are the costs of walk-sharing to varying levels of pedestrian demand and other critical factors representing spatio-temporal preferences of pedestrians?

2. Is it technically viable to implement walk-sharing in a real-world scenario?

4.2 DEVELOPMENT OF A WALK-SHARING MODEL

To test for the technical viability of walk-sharing, the performance of walk-sharing needs to be measured objectively. Performance measurements require performance metrics or costs. These have already been defined in Section 3.6. Additionally, for objectivity, it is necessary to realise the abstract conceptual model presented in Section 3.5. Since it is challenging to collect as well as experiment with real pedestrian behaviour data, complex pedestrian-environment and pedestrian-pedestrian interactions have often been reliably explored through experimentation with computer models (Torrens, Li, and Griffin, 2011). Moreover, in the case of measuring a hypothetical service like walk-sharing, where real data is not available, modelling is the best possible alternative.

An agent-based simulation provides insight into complex, unexpected and non-linear interactions among variables or agents in hypothetical future scenarios (Axtell, 2003). The agent-based approach allows for modelling individual uses of the environment by treating the populations as objects that can interact with the environment and other people (Yin, 2013) and allows the modeller greater control of the experiments by allowing to comprehensively vary all relevant parameters and get a theoretical insight into the complex system behaviours. Past research has shown successful implementation of agent-based models for the investigation of dynamic pedestrian behaviour in urban areas (Schelhorn et al., 1999) and for the purpose of contributing to the study of walkability in urban areas by empirical study of pedestrian behaviours (Bandini et al., 2018; Bandini, Gorrini, and Nishinari, 2016; Gorrini et al., 2017; Huang, White, and Burry, 2017; Yin, 2013). Agent-based simulations have also been useful for addressing problems of online ridesharing and dynamic ridesharing (Bistaffa et al., 2018; Nourinejad and Roorda, 2016; Pelzer et al., 2015).

For developing an agent-based simulation model of walk-sharing, GAMA was the chosen platform. GAMA (GIS Agent-based Modeling Architecture) *"is a modeling and simulation development environment for building spatially explicit agent-based simulations"* (Taillandier et al., 2019). GAML is the language used in GAMA, coded in Java. The major advantage of GAMA is that it has been designed for hassle-free development of agent-based simulation models that are spatial in nature. Hence, GAMA has been widely used by researchers for various projects under the spatial domain, and for pedestrian modelling as well (Iskandar et al., 2020; Lao, 2019).

The model simulates an hour of pedestrian movement along an underlying pedestrian road network which is composed of nodes and edges. Some of the nodes are designated as public transport stops, which constitute the pedestrian agents' destinations. In this study, it has been assumed that all pedestrians start walking from their origins and head towards their corresponding public transport stops. A share of the remaining nodes act as origins of pedestrian agents.

Pedestrian agents become active in the model when the system time equals their intended starting time from their origin. As soon as the pedestrian agents become active, they are included in a matching pool $MP_{D,t}$ of pedestrian agents (Line 1 - Line 5 in Algorithm 3). At a given time step, the model calculates the pairwise spatial Euclidean distance between all agents present in the matching pool. D is composed of two spatial distances, d_1 and d_2. d_1 is the distance between the origins of the two pedestrians while d_2 is the distance between the destinations of the two pedestrians (see Equation 5). Thus D_{P_i,P_j} becomes a measure of spatial proximity between any two pedestrian agents i and j in the matching pool. After the development of a pairwise distance matrix $Mat_{D,t}$ (Line 6 - Line 17 in Algorithm 3) of the matching pool at a given time step, the model starts matching the pedestrian agent pairs in an ascending order of their D. This heuristic approach can always be replaced by an optimisation algorithm. But the intention this study is to look at the principle value and feasibility of the walk-sharing scheme as such, and not regarding optimisation or efficiency of the same. Pedestrians are matched in a pairwise manner, meaning no pedestrian can be matched with multiple pedestrians. The pairwise matching continues till a given threshold of D, D_{th} (e. g., 300 m), has been reached (Line 18 - Line 31 in Algorithm 3) – assuming that people will not walk alone for longer distances without a companion in a system that aims to reduce walk alone length.

After getting matched, the agents are removed from the matching pool (Line 32 - Line 39 in Algorithm 3). Agents may remain unmatched if (i) all their D are greater than D_{th} or (ii) their potential companions were matched with others in lieu of lesser D values. At the next time step, the matching pool is replenished with new pedestrian agents who become active with a new $Mat_{D,t}$ being constructed, and the matching process is repeated. All pedestrian agents are assigned a waiting time threshold WT_{max}, which is the maximum time they are willing to remain in the matching pool after becoming active in the system. The reason behind this is that even if pedestrians want to avail walk-sharing, they will not wait for time periods beyond their preference and will opt for alternatives. Within the scope of this walk-sharing model, it is assumed that these pedestrians will give up and walk alone to their destinations. Hence if waiting time of an agent in the matching pool exceeds WT_{max}, at that time step, the agent is removed from the pool (Line 37 - Line 39 in Algorithm 3). This matching algorithm continues to run on each time step till all pedestrians have either been matched or have exhausted their WT_{max}. The matching algorithm is illustrated in Algorithm 3.

Algorithm 1 Matching algorithm

```
Require: System is characterised by
    • system time $\leftarrow t$
    • time step $\leftarrow t_{step}$
    • Matching pool at time t $\leftarrow MP_{D,t}$
    • Distance matrix at time t $\leftarrow Mat_{D,t}$
    • List of matched agents $\leftarrow L_{matched}$
  Pedestrian agents $P_i$ where each agent is characterised by
    • Starting time $\leftarrow T_{start}$
    • Waiting time threshold $\leftarrow WT_{max}$
    • Matching distance threshold $\leftarrow D_{th}$

for all $P_i \in P$ do                                  ▷ Fill matching pool
    if $t = T_{start,P_i}$ then
        add $P_i$ to $MP_{D,t}$
    end if
end for

for all $P_i \in P$ and $P_j \in P$ do                  ▷ Construct distance matrix
    $D_{P_i,P_j} \leftarrow dist(P_i, P_j)$
end for
Elements on the diagonal and above the diagonal
$\leftarrow largepositivevalue$

$D_{min} \leftarrow min(Mat_{D,t})$                      ▷ Start matching agents
while $D_{min} \leqslant D_{th}$ do
    for all elements in $Mat_{D,t}$ do
        if $D_{P_i,P_j} = D_{min}$ then
            if $L_{matched}$ contains $P_i$ or $P_j$ then
                do nothing
            else
                $L_{matched} \leftarrow L_{matched} + [P_i, P_j]$
                $D_{ij} \leftarrow largepositivevalue$
            end if
        end if
    end for
    $D_{min} \leftarrow min(Mat_{D,t})$
end while
```

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```
24: if $L_{matched}$ contains $P_i$ then        ▷ Agent removal from matching pool
25:     remove $P_i$ from $MP_{D,t}$
26: else
27:     $WT_{P_i} \leftarrow t - T_{start,P_i}$
28: end if
29: if $WT_{P_i} \geqslant WT_{max,P_i}$ then
30:     remove $P_i$ from $MP_{D,t}$
31: end if

32: $t \leftarrow t + t_{step}$                  ▷ Move to the next time state
```

At any time state, after the execution of the matching algorithm, the newly matched pedestrian agent pairs are assigned characteristics that are relevant for the execution of walk-sharing on the road network. First, during the initialisation of the model, the agents are assigned with *walking speeds*. Transport Modelling Guidelines published by VicRoads (`www.vicroads.gov.au`) are referred to in this regard. It is also assumed that walking speeds across the population is normally distributed (VicRoads, 2019). The mean walking speed is set at 4.25 km/h and the standard deviation at 1.0 km/h. After two pedestrian agents are matched to each other, the lower magnitude of the two walking speeds is taken and assigned to both the agents (Line 1 - Line 3 in Algorithm 2). This is done under the assumption that when two people are matched with each other and they walk together, the one with the higher normal walking speed will slow down to accommodate its companion.

Second, based on the starting points (location of the origins) of the two agents, a *meeting point* is set up midway between the agents. The model deduces the shortest path between the origin locations of the two agents and assigns the midpoint of that path as the meeting point (Line 4 - Line 9 in Algorithm 2). The agents will walk this part of the journey alone. Third, if the destinations of the matched agents are not the same, a *separation point* is also deduced which is midway between the respective destinations of the two agents. The method of deducing the separation point is the same as meeting point deduction, with the origins replaced by the destination locations (Line 10 - Line 15 in Algorithm 2). At the separation points, the agents stop walk-sharing and continue walking alone towards their respective destinations, given their destinations do not coincide.

The time state at which two pedestrian agents are matched to each other, with revised walking speeds assigned, waiting times calculated and meeting points deduced, is when the agents start walking. Presuming the general case where the two agents matched with each other have different starting locations, the agents start walking at the same speed (as the lower of the two initial speeds is now assigned to both agents) towards their assigned meeting point. This minor simplification is done to avoid the inclusion of minuscule waiting times (smaller than a minute) that the faster pedestrian encounters after reaching the meeting point early. It is safe to assume that this does not significantly affect the performance of the walk-sharing model. Also, pedestrians may get delayed while reaching the meeting point even if they start on time, due to unexpected stoppages such as waiting at a pedestrian signal. Hence, these are kept beyond the scope of this study.

The matched pedestrian agents follow the shortest path to the meeting point (Line 16 - Line 17 in Algorithm 2). After both the agents have reached their common meeting point, the agents are confirmed to have 'met' and thus start walk-sharing. The agents now follow the shortest path from their designated meeting point towards their common separation point (Line 18 in Algorithm 2). After reaching the separation point, the agents stop walk-sharing and continue walking alone towards their respective destinations (Line 19 - Line 20 in Algorithm 2).

Algorithm 2 Walk-sharing algorithm

```
Require: Two pedestrian agents $P_i$ and $P_j$ from $L_{matched}$ characterised by
    • Walking speed $\leftarrow$ $speed$
    • Origin $\leftarrow$ $(X_o, Y_o)$
    • Destination $\leftarrow$ $(X_d, Y_d)$
$common\_walking\_speed \leftarrow \min(speed_{P_i}, speed_{P_j})$    ▷ Revise walking speeds
$speed_{P_i} \leftarrow common\_walking\_speed$
$speed_{P_j} \leftarrow common\_walking\_speed$

if $(X_o, Y_o)_{P_i} = (X_o, Y_o)_{P_j}$ then    ▷ Deduce meeting point
    $meeting\_point_{P_i,P_j} \leftarrow (X_o, Y_o)_{P_i}$
else
    $shortest\_path\_length_{origins} \leftarrow length(shortest\_path((X_o, Y_o)_{P_i}, (X_o, Y_o)_{P_j}))$
    $meeting\_point_{P_i,P_j} \leftarrow location$ where $length(shortest\_path((X_o, Y_o)_{P_i}, location) = 0.5 * shortest\_path\_length_{origins}$
end if

if $(X_d, Y_d)_{P_i} = (X_d, Y_d)_{P_j}$ then    ▷ Deduce separation point
    $separation\_point_{P_i,P_j} \leftarrow (X_d, Y_d)_{P_i}$
else
    $shortest\_path\_length_{destinations} \leftarrow length(shortest\_path((X_d, Y_d)_{P_i}, (X_d, Y_d)_{P_j}))$
    $separation\_point_{P_i,P_j} \leftarrow location$ where $length(shortest\_path((X_d, Y_d)_{P_i}, location) = 0.5 * shortest\_path\_length_{destinations}$
end if

                                                            ▷ Agent movement
$P_i$ follows $shortest\_path((X_o, Y_o)_{P_i}, meeting\_point_{P_i,P_j})$    ▷ $P_i$ moves to meeting point
$P_j$ follows $shortest\_path((X_o, Y_o)_{P_j}, meeting\_point_{P_i,P_j})$    ▷ $P_j$ moves to meeting point

$P_i$ and $P_j$ follow $shortest\_path(meeting\_point_{P_i,P_j}, separation\_point_{P_i,P_j})$    ▷ $P_i$ and $P_j$ meet and move together towards separation point

$P_i$ follows $shortest\_path(separation\_point_{P_i,P_j}, (X_d, Y_d)_{P_i})$    ▷ $P_i$ moves to destination
$P_j$ follows $shortest\_path(separation\_point_{P_i,P_j}, (X_d, Y_d)_{P_j})$    ▷ $P_j$ moves to destination
```

4.3 PROOF OF CONCEPT USING SYNTHETIC DATA

After the development of the walk-sharing model based on the conceptual model proposed in Section 3.5, it was necessary to investigate whether the developed walk-sharing model, and the conceptual model it is based on, were logically valid. As a *proof of concept*, the developed agent-based model was evaluated using synthetic data. Synthetic data enables the use of predefined values and range of values for all the critical parameters (as stated in Section 3.7) and, thereby, end up with expected results. This helps establish the logical efficacy of the conceptual as well as the agent-based model.

In this regard, the model is fed with synthetic pedestrian road network data and synthetic population data. A square regular grid-shaped network is used with dimensions of 3000 metres x 3000 metres, where each edge has a length of 100 metres. There are a total of 961 nodes and 1860 edges in this synthetic graph. Out of these 961 nodes, 49 are designated as destination nodes ($N_{destination}$) and the rest are origin nodes (N_{origin}). $N_{destination}$ are spread spatially uniformly across the grid at intervals of 500 metres along each dimension, as shown in Figure 4. This is an attempt to roughly reflect the ground conditions of metropolitan Melbourne where 500 metres coincides with average distance between public transport stops. A pedestrian agent population is synthesised, with their origins distributed across the synthetic network, chosen randomly from N_{origin}. The destinations of the pedestrian agents are chosen from $N_{destination}$ while satisfying the chosen *distance to destination* threshold. For example, if $DistanceToDestination_{max}$ is set at 500 m, then the destination of any agent P_i is randomly assigned from the subset of $N_{destination}$ that satisfy $DistanceToDestination_{P_i}$ less than or equal to 500 m. During the cases where there does not exist any suitable destination, the node in $N_{destination}$ closest to the agent's origin is chosen as its destination. During these simulations, the values of critical parameters have been tuned (as stated in Section 3.7).

4.3.1 *Pedestrian demand vs performance*

A greater magnitude of pedestrian demand means that for a person willing to avail walk-sharing, there is a bigger pool of people who are available for matching. The model was ran with varying demand lev-

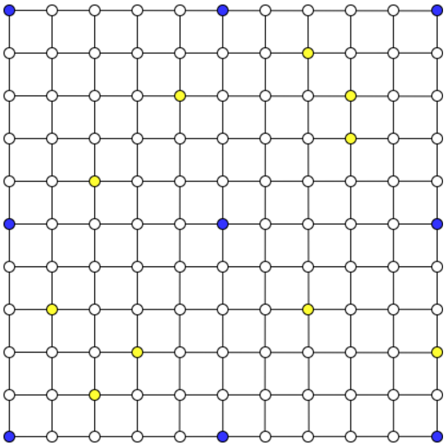

Figure 4: Schematic representation of the synthetic pedestrian road network. The actual network is three times longer along each dimension. Blue nodes form the set $N_{destination}$. Nodes with yellow colour are part of N_{origin} which are origins of pedestrian agents.

els (from 100 people/h to 1000 people/h at intervals of 100 people/h), against two attribute levels of each of the parameters, distance to buddy threshold (200 m, 400 m and 500 m), distance to destination threshold (500 m and 1000 m) and maximum waiting time (300 s and 600 s). Given the pedestrian agent population was synthetically generated, to ensure representativeness of our results, multiple simulations were conducted at each demand level. However, for the sake of sim-

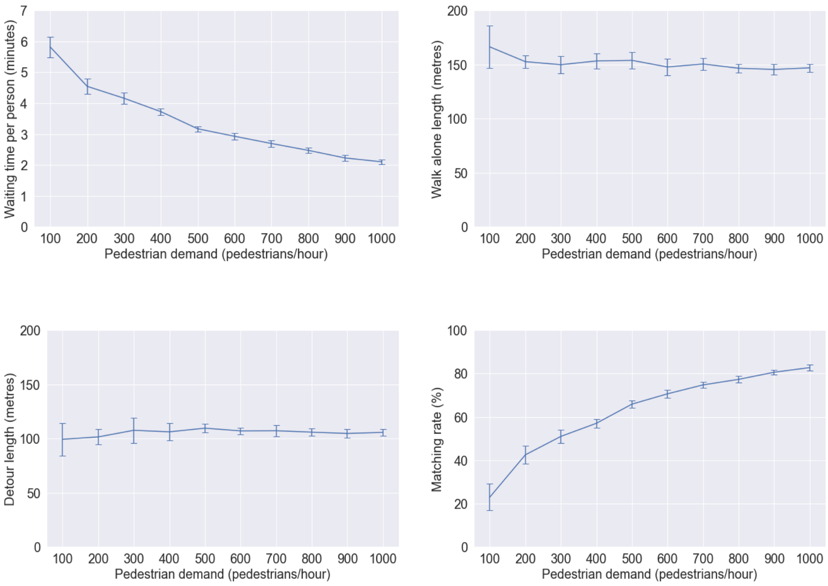

Figure 5: Performance of walk-sharing against varying levels of hourly pedestrian demand against distance to buddy threshold = 500 m, distance to destination threshold = 500 m and maximum waiting time = 600 s

plicity, only the scenario with the following parameter values are presented: distance to buddy threshold = 500 m, distance to destination threshold = 500 m and maximum waiting time = 600 s.

It can be observed from Figure 5 that the relationship between demand and the performance metrics come out as expected. With increasing demand levels, average waiting time has reduced substantially with walk alone length and detour remaining fairly constant. This is because of the thresholds placed on the parameters *distance to buddy* and *distance to destination*. Also, with increased demand, system matching rate has risen significantly. This essentially means that higher pedestrian demands will always improve performance of walk-sharing. It is interesting to observe non-linear relationships between demand, and waiting time and matching rate. Both waiting time and matching rate stabilises after sharp decrease and increase respectively, because there exists situations where matching is not possible even with higher demand levels. These non-linear relationships stem from the existence of multiple space-time thresholds critical to matching, instead of a single one.

The expected nature of non-linear relationships (exponents of the independent variable) is challenging to deduce in complex experimental setups, especially with spatial constraints (agents limited to moving along network edges) and the existence of multiple space-time thresholds based on which matching happens. Yet, with certain assumptions, these can be backed up theoretically. Matching rate (assuming it is inversely proportional to average-inter agent distance in an n-dimensional space), can be shown as proportional to the number of agents in that space raised to the power of the inverse of the number of dimensions. In other words, Matching rate is proportional to $\mathrm{Demand}^{1/3}$, given the agents are distributed across two spatial and one temporal dimension (three in total).

4.3.2 *Distance to buddy threshold vs performance*

A greater distance to buddy threshold means that people willing to avail walk-sharing are more flexible in terms of companion suitability and are willing to get matched to companions spatially farther away. The model was run with varying levels of distance to buddy thresholds (from 100 m to 500 m at intervals of 100 m) against fixed parameter values of distance to destination threshold (500 m), three demand levels (200, 600 and 1000 people/h) and maximum waiting time (600 s). Given the population is synthetic, multiple simulations were conducted for each unique parameter set.

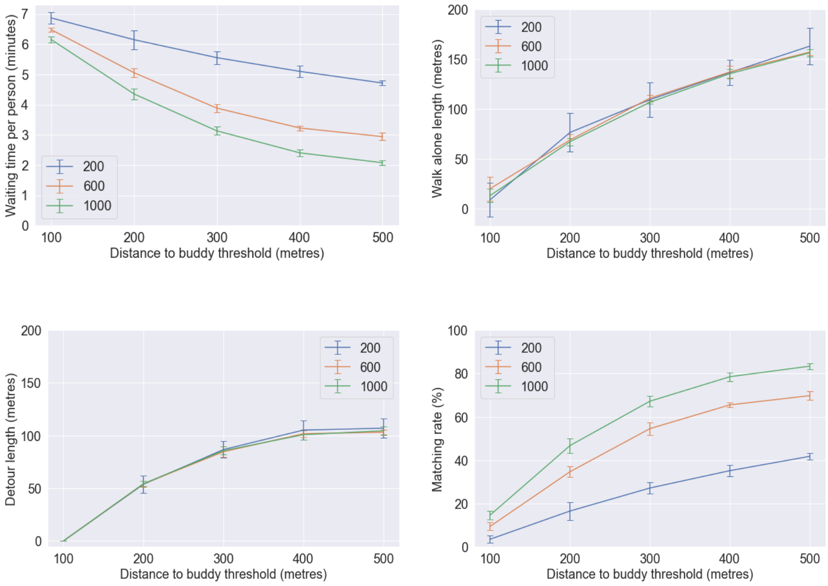

Figure 6: Performance of walk-sharing against varying levels of *distance to buddy threshold* with *distance to destination threshold* = 500 m, *maximum waiting time* = 600 s and *pedestrian demand* = 200,600 and 1000 people/h

It can be observed from Figure 6 that at all three demand levels, as the distance to buddy threshold increases, waiting time reduces significantly in lieu of farther yet quicker matches, while matching rate increases substantially as pedestrians get matched before their maximum waiting time is exhausted. Non-linear relationships are observed due to the existence of matching criteria other than distance to buddy. On the costlier side, both detour length and walk alone length increase significantly, given the matches are quicker, but farther away. Here also, non-linear relationships are observed between the matching distances and distance to buddy threshold. It must be noted that while a low distance to buddy threshold would result in only low walk alone distances and low detour lengths, high thresholds would result in matches where both high and low walk alone distances and detour lengths are possible. Especially due to the chosen heuristic of the matching algorithm (Line 18 - Line 31 in Algorithm 3), where matches start in ascending order of distance to buddy, matches resulting in lower walk alone distances and detour lengths always occur, even when the distance to buddy threshold is high. Hence, a higher threshold does not necessarily result in higher matching distances.

This restricts the matching distances from shooting up linearly and thus the non-linear relationships are observed.

4.3.3 *Distance to destination threshold vs performance*

A higher magnitude of distance to destination threshold means that pedestrians have destinations across a greater range of distance from their origins. Therefore, longer walking trips are now accommodated. The model was run with varying levels of distance to destination thresholds (from 100 m to 700 m at intervals of 100 m) against fixed parameter values of distance to buddy threshold (500 m), three demand levels (200, 600 and 1000 people/h) and maximum waiting time (600 s). Given the population is synthetic, multiple simulations were conducted for each unique parameter set.

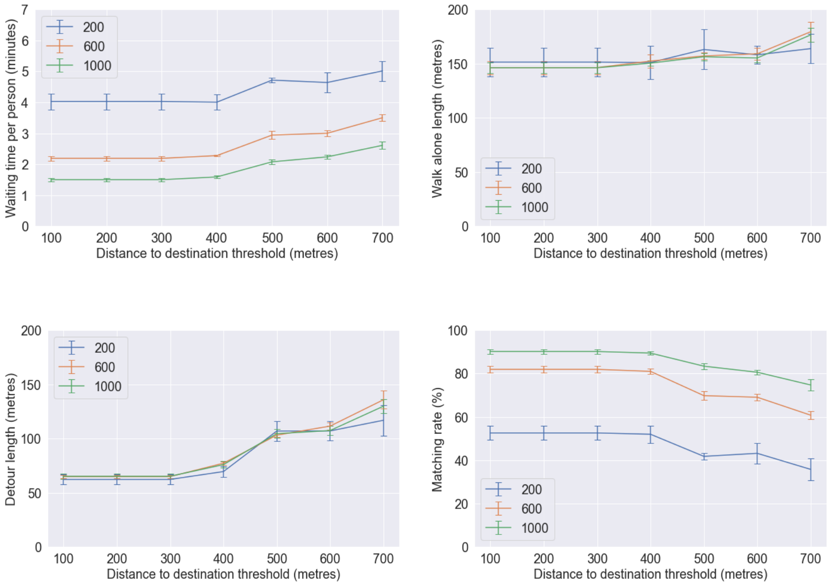

Figure 7: Performance of walk-sharing against varying levels of *distance to destination threshold* with *distance to buddy threshold* = 500 m, *maximum waiting time* = 600 s and *pedestrian demand* = 200, 600 and 1000 people/h

It can be observed from Figure 7 that at all three demand levels, as the distance to destination threshold increases, the average waiting time gradually increases as well, as destinations farther away from the origin means lesser chances of finding a suitable companion, given distance between destinations between two potential companions are also important. For the same reason, as the matching rate goes down, the walk alone length goes up slightly and the detour length increases as well. This essentially means that longer walking trips in walk-sharing prove costly in terms of all four performance metrics, and reduces the appeal of walk-sharing.

It can be noted that the performance of walk-sharing dips only after 400 m. This is due to the configuration of public transport (PT) stops in our assumed grid which are spaced 500 m apart. Hence, when *distance to destination threshold* is 400 m or less, performance remains the same since agents always choose their nearest PT stops. When the threshold exceeds 400 m, the agent is allowed to choose a PT stop that may not necessarily be the nearest one. Also, the reason for observing similar performance in the range of 100 m to 400 m is the destination assignment rule of our algorithm, where the agent is free to choose a destination outside the set threshold if there are no PT stops within it. Hence, in the range of 100 m to 300 m, agents choose their nearest PT stop, often violating the *distance to destination threshold* if necessary (at 400 m, violation is not necessary), and thus show similar performance.

4.3.4 *Maximum waiting time vs performance*

A higher threshold for maximum waiting time means that the pedestrians are willing to wait for longer periods of time to get matched to a suitable companion, thereby improving their chances of getting matched to others who are spatially less distant, but temporally a bit more apart. The model was run with varying levels of maximum waiting time (300, 600 and 900 s) against fixed parameter values of distance to buddy threshold (500 m), distance to destination threshold (500 m) and three demand levels (200, 600 and 1000 people/h). Multiple simulations were conducted at each demand level.

It can be observed from Figure 8 that as the maximum waiting time allowance increases for all pedestrians, the average actual waiting time of pedestrians increases, as they are now willing to wait longer for a match before giving up. It can be noted that at a lower demand level, the increase is substantial as pedestrians usually use their additional waiting time allowance for a match, given a relatively smaller matching pool. For a higher demand level, the increase is not significant, as people tend to get matched without the need for using their additional waiting time allowance, given the abundance of people around. The average detour length and walk alone length remain

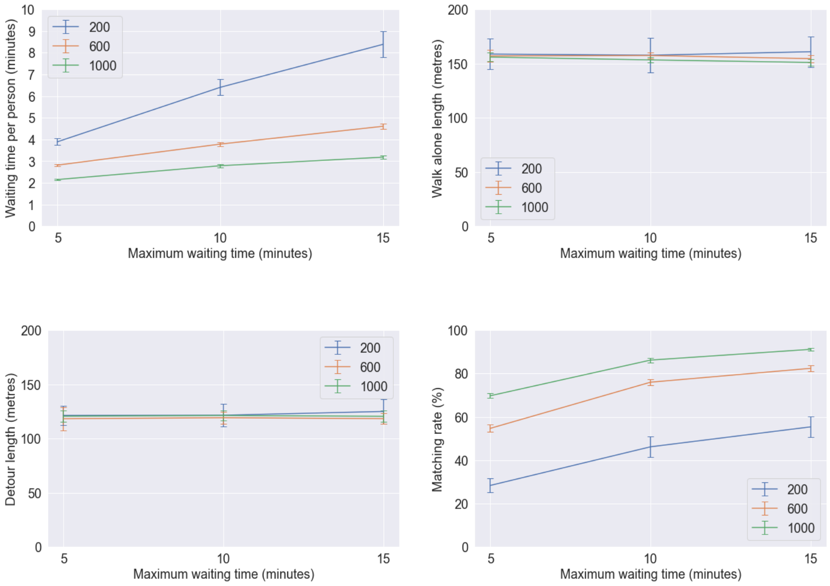

Figure 8: Performance of walk-sharing against varying levels of *maximum waiting time* with *distance to buddy threshold* = 500 m, *distance to destination threshold* = 500 m and *pedestrian demand* = 200, 600 and 1000 people/h

fairly constant, as they are mostly dependent on spatial flexibility as compared to temporal flexibility of the agents. The matching rate of the system increases at all demand levels, and understandably so, as people are waiting longer which increases the likelihood of them finding a match.

4.3.5 *Proof of concept*

The results obtained by running the agent-based walk-sharing model under various theoretical, yet plausible scenarios clearly prove that the model is effective in projecting the proposed walk-sharing scheme. Although synthetic datasets may not be fully representative of actual human behaviour, it helps in the understanding of the general trends in relation to the sensitivity between different variables. In this case, under controlled conditions of synthetic data, there is evidence that this walk-sharing model yields reasonable outcomes and intuitive trends that provide a foundation to develop a more complex walk-sharing model that incorporates actual pedestrian preferences and real-world data. In the following section, exit counts of people from buildings from the University of Melbourne Parkville campus is employed to investigate the technical viability of walk-sharing in a real-world scenario.

4.4 TESTING THE TECHNICAL VIABILITY OF WALK-SHARING USING REAL DATA

4.4.1 *Campus Wi-Fi data*

Universities collect Wi-Fi access data on their campus for space management purposes. Whenever a device probes in to the Wi-Fi network, the probing event is recorded (along with some relevant additional data) and stored in the university's database. Typically only the identity of the Wi-Fi receiver is known, but not their location in the environment. But these receivers are coded with information of their own location in terms of the building number and floor level, such as Building 176, Level 2. Each probing event record contains the location attribute of the receiver where the device probes and hence, each record is a piece of spatial data, albeit with relatively poor granularity compared to GNSS data or other modern positioning technologies. For this study, a temporally limited and totally anonymised subset of the Wi-Fi access data of a university campus was obtained.

This subset contains the last daily probing event of every device held by staff and students from buildings inside the Parkville campus of the University of Melbourne for every day of the year 2019. The dataset contains 12.14 million *last seen* records for 2019 (a total of 351 days), that is roughly 34k *last seen* records per day with 208,667 unique devices probing throughout the year. It was assumed that these daily *last seen* dataset can act as a reasonable proxy for daily exits of all staff and students on campus, and thereby provide representative exit counts of people, at different locations (up to building granularity) and different times (up to minute granularity). This means that each *last seen* record of a device is the location and time of exit of the owner of the device from a building on campus.

Static devices had been filtered out by the dataset providers, as well as probing events to outdoor Wi-Fi receivers. The goal was to have a realistic estimate of spatio-temporal exit counts of people and not devices. Since people usually carry more than one device with themselves that is connected to the Wi-Fi network (e. g., a smartphone and a laptop), an analysis was necessary to estimate the number of people from the number of probing events. Due to privacy concerns, access to the personal level data was not granted by the dataset providers, and hence identifying multiple records resulting from a single person was challenging. Hence, a preliminary analysis was conducted by the dataset providers at the university to estimate the average device to person ratio for the entire dataset, given their access to privacy-sensitive personal data as well. They arrived at an average value of 1.8 devices per person. Hence, 45% of the records for any given hour of a given day were removed randomly (based on the obtained ratio of 1.8 devices per person) before conducting the simulation.

To ensure representativeness of the set of records, multiple simulations for each scenario were conducted and the average values of the resultant performance metrics were obtained. Three days were considered for these simulations, 2nd February, 21st November and 11th April, as they corresponded with the 5th percentile, 50th percentile and 95th percentile of daily exit record counts, respectively. The hourly variation of the number of exit records after preprocessing (removal of duplicate entries) is shown in Figure 9. Pedestrian network information around the university campus was imported from OpenStreetMap using the Python package OSMnx (Boeing, 2017). The network is illustrated in Figure 20.

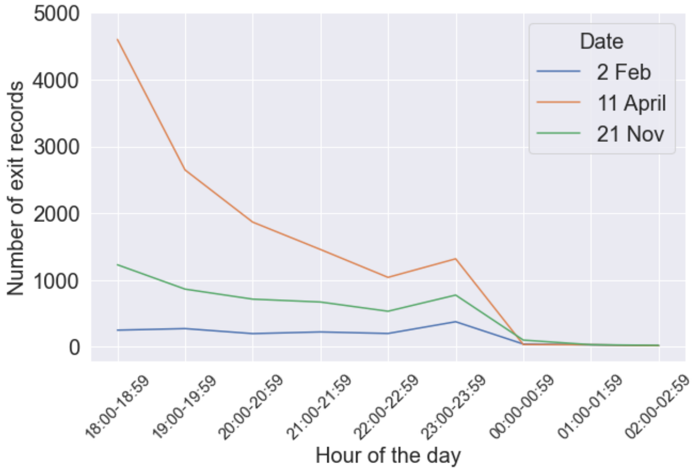

Figure 9: Number of Wi-Fi exit records of the chosen days by hour

Figure 10: Pedestrian network in and around Parkville campus of University of Melbourne; green squares = tram stops, orange squares = bus stops

4.4.2 *Choice of destination*

Since *last seen* records are considered as a proxy for people exiting the buildings of the university for the last time on a given day, it was assumed that people consequently embark on their journey back home, either directly or indirectly (e. g., via the supermarket). For this study, it was assumed that all journeys are made via public transport (given the majority of the records potentially represent students) and hence the first leg of this journey constitutes walking from the exit building to the intended public transport stop. Since the primary interest lies in the first leg of this trip, the destination for each person was assumed to be a nearby public transport stop.

The assumption of all departing people availing public transport is not robust, and may result in slight overestimation of the pedestrian population in a given time interval. But given that *technical viability* of walk-sharing is being investigated (whether walk-sharing is spatio-temporally possible at critical times of the day in a real-world scenario with everyone willing to avail it), this assumption is not inappropriate, and will not produce results that are misleading. The use of public transport as the only mode of travel is assumed simply to gauge approximate, yet representative destinations of agents, without the availability of relevant destination data. However, the choice of mode does not govern the performance of walk-sharing in any manner for this baseline scenario. On the contrary, this model will serve as a baseline which can be further calibrated with actual spatio-temporal and social preferences of people and also the ambient environmental factors. Thus, these simulations will still yield interesting insights on how walk-sharing could perform in a given scenario, if it is implemented in future. Location information and other metadata of PT stops were imported from OpenStreetMap using the Overpass Turbo API (`https://github.com/tyrasd/overpass-turbo`).

4.4.3 *Parameter value selection*

For checking the technical viability of walk-sharing in a real-world scenario, certain assumptions were made on the fixed values of the relevant parameters for the simulation. People will tend to avoid large detours when the destination is not too far, to minimise their perceived cost-benefit ratio. Hence, *distance to buddy threshold* was set at 200 m. Also, intended public transport stops for most people will lie within 700 m. This maximum threshold was arrived at based on multiple sample measurements in the university study area (approximately the longest side measurement of the study area). People may usually have sufficient temporal flexibility given they are returning home, and hence the *maximum waiting time* is kept fixed at 600 s. Finally, all public transport stops around the Parkville campus either serve buses or trams. Referring to VISTA (Victorian Integrated Survey of Travel & Activity) data from 2012-2016, it was inferred that of all walking trips made to public transport stops (excluding train stations) in the City of Melbourne (the Local Government Area where the Parkville campus of the University of Melbourne is located), roughly 80% walk to tram stops while the rest 20% walk to bus stops. The after-dark hours were considered for simulation. Hence, the simulations were run for 9 hours, from 6 PM in the evening to 3 AM in the morning.

To summarise, the following parameter values were selected for the simulations.

- Distance to buddy threshold = 200 m
- Distance to destination threshold = 700 m
- Maximum waiting time = 600 s
- Probability of choosing tram stop = 0.80
- Probability of choosing bus stop = 0.20

4.4.4 *Results and discussion*

Using the aforementioned parameter values, the walk-sharing model was fed with the preprocessed Wi-Fi *last seen* records. Multiple simulations were conducted for each scenario to reduce randomness to ensure representativeness of the results. The results illustrated in Figure 11 were obtained from averaging the magnitudes of the performance metrics. It can be observed that both *waiting time per person* and *matching rate* remains relatively stable from 6 PM till midnight, with performance dipping afterwards. This can be attributed to the

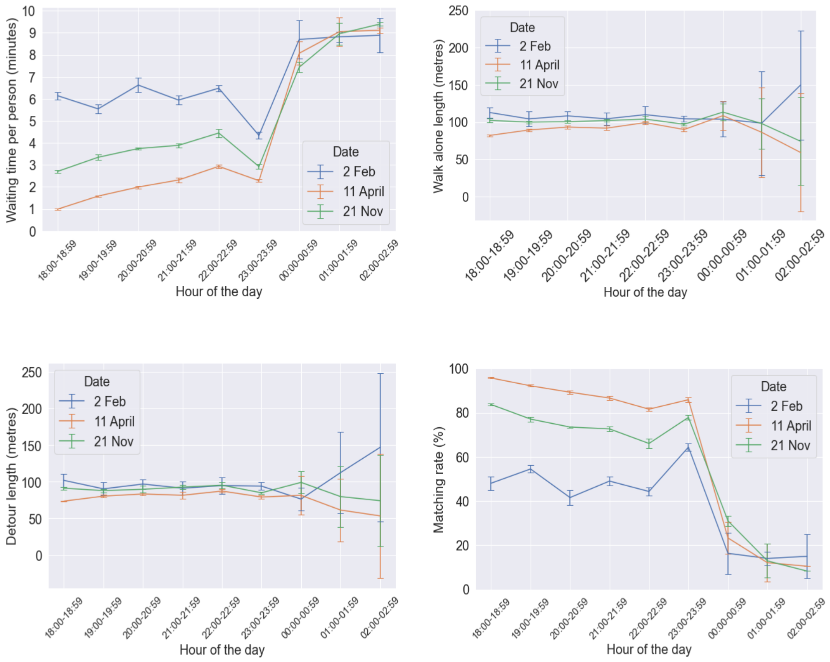

Figure 11: Performance of walk-sharing in the University of Melbourne Parkville campus from 6 PM to 3 AM with *distance to buddy threshold* = 200 m, *distance to destination threshold* = 700 m and *maximum waiting time* = 600 s

hourly variation of the number of exits as can be seen in Figure 9. *Waiting time per person* for the entire population increases drastically after midnight and the *matching rate* goes down significantly as well. The performance of walk-sharing in terms of *waiting time per person* and *matching rate* on 21st November and 11th April remains acceptable till midnight. While *waiting time per person* remains below 5 minutes, *matching rate* remains above 70% at all times. For 2nd February, *waiting time* ranges from 4 to 7 minutes while *matching rate* varies from 40 to 60%. In that same time interval, per capita *detour length* and *walk alone distance* for the matched population remain relatively stable across the three days, similar to Figure 5.

While it was discussed how walk-sharing can be beneficial to the community, simulation using real data is useful for quantifying these benefits by obtaining more realistic and meaningful results. Two metrics that attempt to measure safety improvement objectively, are introduced in this context.

- **Walk alone length saved:** The primary purpose of walk-sharing is to reduce the fear of victimisation of pedestrians by making people walk together instead of walking alone. This is because people feel safer with a companion even in environments where they would otherwise feel vulnerable. Thus, safety enhancement is directly proportional to the distance people walk with a companion, which without walk-sharing, they would walk alone. *Walk alone length saved* is the difference between the distance covered by a person to reach their destination alone in the absence of walk-sharing, and the distance they have to walk alone while availing walk-sharing. The greater the magnitude of *walk alone length saved*, the higher is the impact of walk-sharing in terms of safety enhancement.

$$\begin{aligned} WalkAloneLengthSaved_{P_i} = {} & L_{origin,destination} \\ & - WalkAloneLength_{P_i} \end{aligned} \tag{9}$$

- **Safety index:** *Safety index* is the mean *walk alone length saved* per capita expressed as a percentage of the distance walked by a person in the absence of walk-sharing. Thus *safety index*, like *walk alone length saved*, is another proxy for measuring the magnitude of safety enhancement of walk-sharing. The rest of the thesis proceeds with *safety index* as the chosen performance metric representing the objective safety enhancement via walk-sharing.

$$\begin{aligned} SafetyIndex = 100 * (WalkAloneLengthSaved_{mean} \\ /L_{origin,destination,mean}) \end{aligned} \quad (10)$$

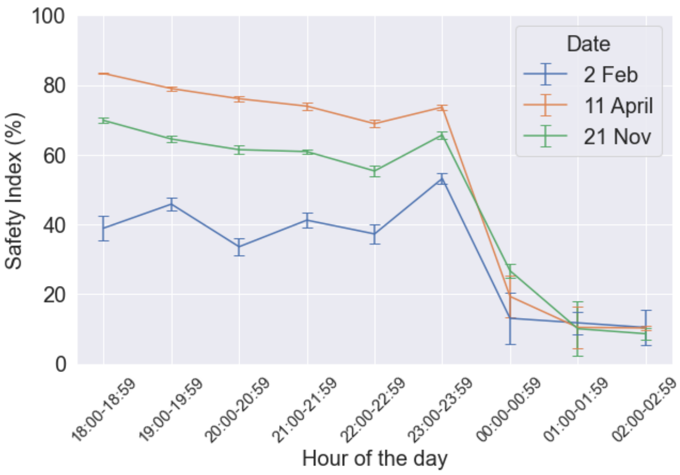

Figure 12: Safety enhancement of walk-sharing the University of Melbourne Parkville campus from 6 PM to 3 AM with *distance to buddy threshold* = 200 m, *distance to destination threshold* = 700 m and *maximum waiting time* = 600 s

It can be observed from Figure 12 that from 6 PM till midnight, walk-sharing is able to reduce 40 to 80% of walking distance that has to be covered alone in the absence of walk-sharing (in the range of 200 to 500 m, given the average walking distance without walk-sharing is roughly 630 m). Given 21^{st} November is the median, walk-sharing is able to reduce more than 60% of walk alone distance for half of the days of the year in the university scenario. The results point towards significant safety enhancement via walk-sharing. It must be noted that the obtained results are based on the assumption that all the pedestrian agents are willing to accept walk-sharing, given it meets certain acceptable spatio-temporal thresholds. Given that in the real-world, 100% acceptance rate is not feasible, the results of safety enhancement of walk-sharing are apparently exaggerating. It will be interesting to explore acceptance rates in a future study based on modal shifts (people switching from car to walk-sharing, walking alone to walk-sharing), and therefore, the implications on calculating a safety index. But this cannot be understood without having knowledge about the preferences of the community in the context of walk-sharing. However, the obtained results are valuable nonetheless as they effectively state the capacity of walk-sharing in terms of pedestrian safety enhancement. So, by stating that walk-sharing can, at times, improve safety by 80%, a likely maximum value has been obtained.

Safety and perceived safety are subjective terms. Therefore, measuring safety improvement quantitatively is a challenging task, is not trivial, and hence always require justified assumptions. A major objective of this thesis is to objectively measure the potential for safety improvement of walk-sharing. In that regard, this thesis uses a proxy measure viz., *safety index*. Safety index is based on the assumption that companionship guarantees improvement in safety. However, trust in that companion is key to feelings of safety as well. For example, women may want to participate in walk-sharing, only if their walking companion is another woman, as they may perceive unknown women as less of a threat than their male counterparts. Therefore, the safety index achieved above is subject to revision based on actual social preferences of people who wish to participate in walk-sharing. The following chapter showcases the results obtained from an online public survey conducted to understand such spatio-temporal and social preferences of the community with respect to walk-sharing.

4.5 CONCLUSIONS

In Chapter 3, the theoretical foundations of walk-sharing were established. But the performance of walk-sharing under different plausible urban scenarios needed to be investigated before claiming its suitability for the community. It was hypothesised that walk-sharing will be beneficial to the community with acceptable levels of costs, even at critical times of the day. This chapter presented the materialisation of the conceptual walk-sharing model into an agent-based model for objective measurement of performance, proved the logical efficacy of the model by using synthetic data, and finally tested the technical viability of walk-sharing using real human mobility data. In the first step, the logical efficacy of the developed walk-sharing model was proven by testing it with varying levels of synthetic data on a synthetic pedestrian network. After observing intuitive trends on all fronts, proof of concept was established.

In the second step, university's Wi-Fi tracking data was used to understand how walk-sharing could perform in a real-world scenario. After preprocessing the dataset, representative hourly counts of people exiting buildings on campus for the final time in a day were obtained. Using this information, the model was run at critical hours of the day under three scenarios (low, median and high exit count days). After analysing the results, it was observed that walk-sharing produced apparently acceptable values of performance metrics (and hence, technically viable) till midnight, especially for the median and high exit count scenarios. This meant that at least for 50% of the time, walk-sharing was technically viable with minor spatio-temporal costs. The performance metrics till midnight were acceptable, even for the low exit count scenario. In terms of safety enhancement, it was observed that walk-sharing was able to increase the safety perception of pedestrians by 40 to 80% in almost all cases (more than 60% for half of the time), with the improvement being measured using the percentage of walk alone length it saved. Given that a social walk-sharing setup is cost-effective and a proactive intervention, and could be setup in minimal time, the safety enhancement performance of walk-sharing looks more than promising.

There were certain limitations of this chapter that need to be highlighted as well. Only the technical viability of walk-sharing was investigated in this chapter, meaning the performance was measured based on justified, but assumed, spatio-temporal parameter thresholds. Establishment of technical viability was a necessary first step of checking for the viability of this novel walk-sharing scheme. However, its community acceptance is still not verified. Walk-sharing was simulated under the assumption that all people (staff and students of the university campus) are willing to participate walk-sharing. But the scope of this chapter did not involve looking at social preferences of people, such as trust in companion or demographic preferences, etc.

Success of walk-sharing, and its consequent practical viability and effectiveness to improve safety, will be significantly dependent on the preferences of its possible end-users, which is the people in the community. Whether the public would like to participate in walk-sharing, and under what conditions, can only be understood from conducting a survey. The results of such a survey will provide relevant insights, and using these from the surveys as inputs, social preferences can be added to the base walk-sharing model for calibration purposes. This will lead to making more informed decisions on setting realistic spatio-temporal parameter values in the model, and thus calibrate it to obtain more representative results. To address these limitations and proceed towards the investigation of practical viability and effectiveness of walk-sharing, the following chapter discusses the process of designing and conducting such a survey, and more importantly, presents the key findings in detail.

5

COMMUNITY PREFERENCES ON WALK-SHARING

*This chapter is based on the manuscript "**Investigating the practical viability of walk-sharing in improving pedestrian safety**" published in* Computational Urban Science *by Bhowmick, Winter, Stevenson and Vortisch (2021). My contribution as the first author of this manuscript includes proposing the hypothesis and the research problem, designing a systematic literature review method, design and implementation of research methods, analysing the results and presenting the discussion and conclusions. These works were supervised by Prof. Stephan Winter (my primary supervisor at The University of Melbourne), Prof. Mark Stevenson (my co-supervisor at The University of Melbourne), and Prof. Peter Vortisch (my primary supervisor at Karlsruhe Institute of Technology) who provided feedback and suggestions at every stage of this study.*

The practical viability of walk-sharing is largely dependent on community acceptance, which has not, until now, been explored. Walk-sharing is intended to improve the safety perception of people in relation to walking, reduce fear of crime, and thereby improve urban liveability. Hence, it is necessary to investigate the perceptions and understand the preferences of these people in the community, who are the potential end-users of this proposed walk-sharing scheme. Gaining useful insights on the community's spatio-temporal and social preferences will eventually ensure the establishment of practical viability of walk-sharing in a real-world urban scenario. This chapter discusses about the survey that was conducted to obtain useful insights on how people could perceive walk-sharing. While it was established in the previous chapter that walk-sharing is technically viable in a certain real-world scenario, community preferences in our agent-based model were not accounted for. To obtain information on public feedback and perception about walk-sharing, a survey was deemed necessary. Given that walk-sharing is a novel and hypothetical matching service which is in its conceptual stage and far from realisation, a first of its kind, stated-preference survey was conducted. Similar stated-preference (SP) surveys are well-established in the urban and transportation planning domain, given the greater amount of control researchers have while defining the conditions and the flexibility of defining new variables (Kroes and Sheldon, 1988). SP surveys can help understand a respondent's evaluation of a product or service, especially in cases where the product or service in question, are hypothetical.

5.1 RESEARCH QUESTIONS

This chapter aims to answer the following research questions.

- What is the likelihood of walk-sharing uptake in the community?
- What is the extent of spatio-temporal compromises that people are willing to make to participate in walk-sharing?
- Are there any social preferences related to choice of walking companion that may affect the uptake of walk-sharing?
- Do socio-demographic characteristics influence the preferences of people related to walk-sharing?

5.2 SURVEY INSTRUMENT

A questionnaire survey was designed for this purpose and was launched on *Amazon Mechanical Turk*, an online commercial survey platform (`https://www.mturk.com/`). The recruitment was confined to respondents who, at the time of the survey, resided in urban and suburban locations in Australia, were above 18 years of age, and did not require assistance while walking. Participation in the survey was voluntary. To encourage participation, the respondents were paid 7 Australian Dollars each, an amount that was above the existing minimum national wage rate, considering the expected time required to complete the survey. The survey was live from June 2020 through October 2020. During that period, it had collected responses from 234 participants. The respondents were briefed about the proposed walk-sharing scheme before starting the survey. The survey had collected data related to the attitude of the respondents towards the proposed walk-sharing scheme, and also their spatio-temporal and social preferences in this regard. The survey had also collected socio-demographic data of the participants to investigate the effect of demographic groups on a participant's affinity towards walk-sharing.

5.3 SAMPLE CHARACTERISTICS

The demographic characteristics of the 234 respondents have been illustrated in detail in Table 1. The proportion of each demographic subgroup is shown in the table. The respondents were predominantly male (69%) and belonged to the age bracket of 25-44 years (62%). Around 76% of them identified English as their preferred language in household communications and 53% were born in Australia. A little over 67% of the respondents had an educational qualification of Bachelor's degree or above, more than 60% were working, with uniform representation across income levels. Almost 71% of the respondents had access to a vehicle, and most people used either private motorised or public transport for commute. When it comes to travelling to the supermarket, around 52% of people use private motorised transport, while 37% of people choose walking as their preferred mode of travel.

Characteristic	Categories	Respondents (count)	Respondents (%)
Age	18-24	78	33.3
	25-44	145	62.0
	45-64	11	4.7
Gender	Female	70	29.9
	Male	162	69.2
	Other	2	0.9
Educational qualification	Bachelor's degree level and above	158	67.5
	Certificate level IV or III or Advanced Diploma and Diploma level	31	13.2
	Year 12 or below	45	19.2

Employment status	Full-time student	53	22.6
	Unemployed	39	16.7
	Work full-time	86	36.8
	Work part-time	56	23.9
Weekly income	0 - 500 AUD	92	39.3
	1001- 2000 AUD	46	19.7
	501 - 1000 AUD	77	32.9
	More than 2000 AUD	19	8.1
Number of vehicles	None	40	17.1
owned	1	81	34.6
	2	77	32.9
	3	17	7.3
	More than 3	19	8.1
Whether has access to	Yes	166	70.9
a vehicle	No	68	29.1
Place of birth	in Australia	126	53.8
	outside Australia	108	46.2
Household language	English	178	76.1
	Any other European language	17	7.3
	Non-European language	39	16.7
Mode of travel to work	Bicycle only	12	5.1
	Private motorised transport (Car, Motorbike) as a driver or a passenger	86	36.8
	Public transport	107	45.7
	Cab	1	0.4

	Walk only	28	12.0
Mode of travel to supermarket	Bicycle only	7	3.0
	Private motorised transport (Car, Motorbike)	121	51.7
	Public transport	15	6.4
	Cab	3	1.3
	Walk only	88	37.6

Table 1: Demographic characteristics of respondents.

5.4 KEY FINDINGS AND DISCUSSION

5.4.1 *Spatio-temporal preferences*

Waiting time is the duration for which a person willing to avail walk-sharing waits before getting matched with a walking companion. The respondents were asked about the maximum time they would prefer to wait to get matched to a walking companion. The results are shown in Figure 13. It can be observed that, except a small fraction of people who say that they are not willing to wait at all, the majority are willing to wait ranging from 1 to more than 15 minutes, which is positive for walk-sharing. It can be seen in Figure 13 that most of the respondents are either willing to wait up to 5 minutes or 10 minutes, while a significant share of respondents have stated their willingness to wait beyond 15 minutes as well. Interestingly, more people are willing to wait for more than 15 minutes than people who have a maximum waiting time threshold between 11-15 minutes.

Detour time is a resultant of pedestrians accommodating for their companion's travel route. Since pedestrians will not walk directly from their origin to their destination, there will be an amount of detour involved. This extra time required to travel to their destination is the detour time. Hence, the respondents were also asked about the maximum detour they are willing to accept when availing walk-sharing. The results are shown in Figure 13. It can be observed that most people (over 50%) admit to a maximum detour time of 0-5 minutes while some are willing to accept longer detours.

Figure 13: Distribution of responses on temporal preferences

The next step was to understand whether demographics played a part in governing maximum waiting time and maximum detour time preference stated by the respondents. Since the respondents were not asked for discrete values of maximum waiting time or detour time, determinate quantitative analysis was not trivial. Hence, visual inspection was carried out to understand whether the distribution of maximum waiting time and maximum detour time was different, across demographic subgroups.

For waiting time, visual differences between the stated waiting time distributions of respondents born in Australia and outside Australia were observed. This can be observed from from Figure 14 where it can be clearly seen that the respondents born in Australia seem to be more flexible in terms of their waiting time thresholds. 35% of those respondents are willing to wait for more than 15 minutes to avail walk-sharing under critical circumstances, while the corresponding figure is 21% for the respondents born outside Australia. Chi-square test was conducted and the result suggested that the distributions of waiting time were dependent on where the respondents were born at 90% CI (chi-squared = 6.62, p = 0.08). This could be due to cultural differences in safety perception among these two demographic groups. But no substantial evidence of this sort could be found in the ridesharing and shared mobility domain. On the other hand, sufficient evidence to explain detour time threshold as a function of any socio-demographics of the respondents was not found.

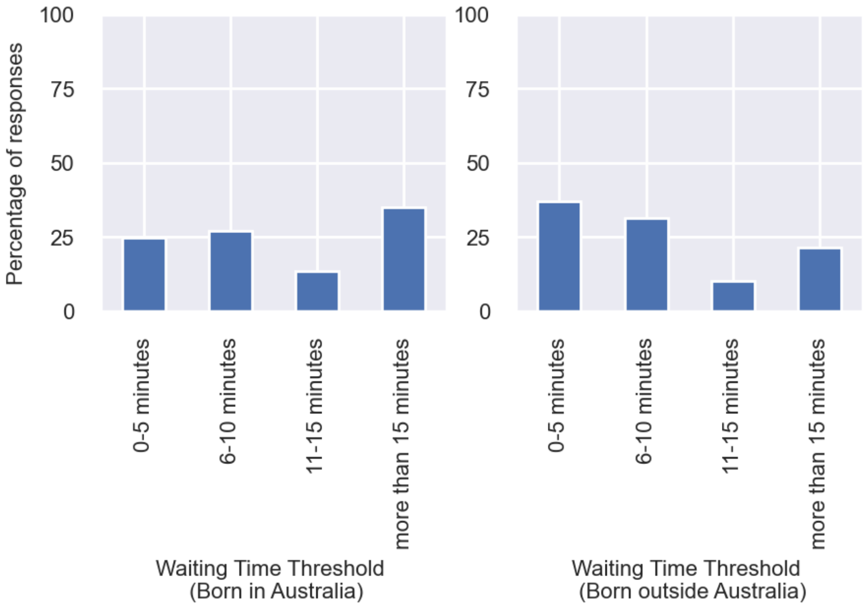

Figure 14: Distribution of responses on maximum waiting time by place of birth

Respondents were also asked the times of the day where they would prefer to avail walk-sharing. It can be observed from Figure 15 that many of the respondents have stated that they would prefer to avail walk-sharing in the evening. This could be due to the fact that it gets dark during the evening, and it coincides with a significant amount of pedestrian movement, especially the last leg of people's journeys back home after a day's work or study.

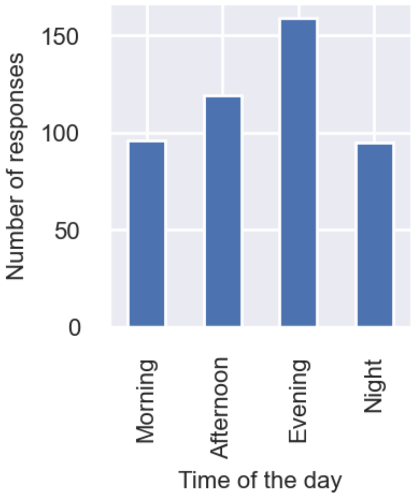

Figure 15: Distribution of responses on preferred time of the day to avail walk-sharing

5.4.2 *Social preferences*

It was expected that there exists possible social preferences along with spatio-temporal preferences when it comes to walk-sharing. In other words, people may have certain preferences when it comes to the socio-demographic characteristics of their companion. The survey participants were asked about their preferences when it comes to the age, gender and ethnicity of their walking companion. The distribution of the responses have been illustrated in Figure 16.

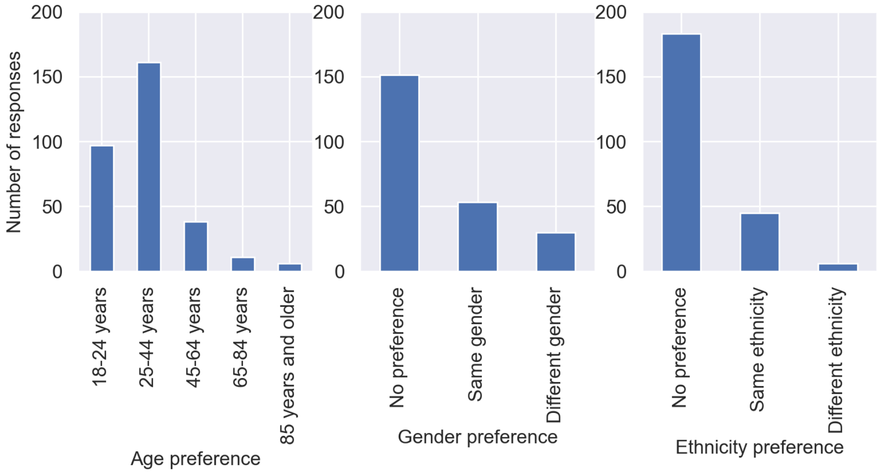

Figure 16: Distribution of responses on social preferences

It can be observed that the most commonly preferred age groups are 18-24 years and 25-44 years. Given that 85% of respondents belong to these to age groups, it becomes clear why the companion preferences belonging to these two age groups are high. Overall, this shows that people would prefer to have a walking companion who is roughly in the same age group. This could be due to similar mobility attributes such as walking speed and greater chances of socialising during walk-sharing. In terms of gender and ethnicity preferences, majority of the respondents stated that they do not have any preferences, more so for ethnicity.

It was also investigated whether the social preferences of the respondents were influenced by their demographics. After cross-tabulating the three social preferences (age, gender and ethnicity) with all the attribute levels of each demographic variable, no significant relationship could be found except for gender preference, which was found to be significantly varying with the gender of the respondent. It can be observed from Figure 17 that a little less than half of the female respondents stated that they would prefer their walking companion to be of the same gender, which was significantly larger as compared to the 10% of male respondents who said so. In other words, women would be inclined towards walk-sharing more when their assigned walking companion would be another woman. This has been historically observed in ridesharing surveys where women respondents have stated that they felt safer when their co-passenger was another woman, as compared to a man (Meshram, Choudhary, and Velaga, 2020). Furthermore, women's focus of fear in the context of personal safety in outdoor environments is mostly men (Lorenc et al., 2013).

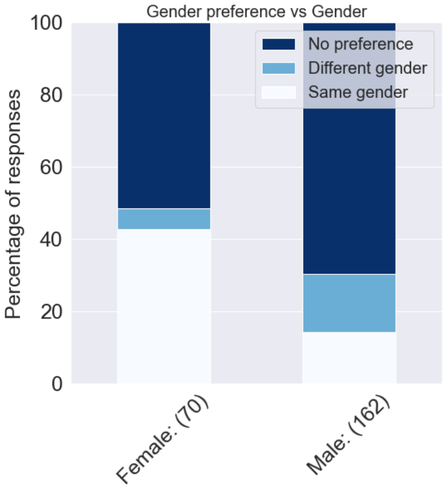

Figure 17: Distribution of responses on gender preference of walking companions

5.4.3 *Likelihood of availing walk-sharing*

After investigating the responses of the participants with regards to their spatio-temporal and social preferences, it was also necessary to understand their overall likelihood towards walk-sharing. Hence, the respondents were asked to state how likely they are to avail walk-sharing on a Likert Scale of 0 to 4, 0 being *Highly unlikely* and 4 being *Highly likely*. It can be observed from Figure 18 that responses of the respondents is well-distributed across the Likert scale with most of the respondents stating they are *Neutral* to *Likely* to avail walk-sharing.

In contrast, when the respondents were asked whether they are willing to offer walk-sharing, given that other people might exist who need to avail it, people responded more positively, with significant improvement in the share of people who stated *Highly likely*. This indicates that a portion of people feel that they are relatively confident while walking alone, but at the same time, are willing to participate in walk-sharing to assist others in need.

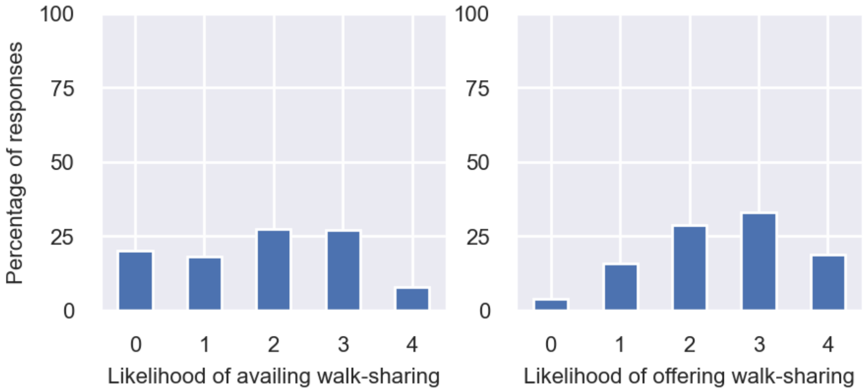

Figure 18: Distribution of responses on likelihood of availing and offering walk-sharing (0 = Highly unlikely, 4 = Highly likely)

Consequently, the question arose that whether demographics drive the likelihood of taking up walk-sharing. Both one-way ANOVA (ANalysis Of VAriance) and independent samples t-test were employed to investigate whether the mean likelihood scores, calculated using the mean of the stated responses against likelihood of taking up walk-sharing, were significantly different across any demographic groups. The tests were conducted using the governing demographics *age, gender, educational qualification, employment status and existing mode of travel*.

By employing both ANOVA and the t-test, it was observed that the *existing mode of travel* is the only factor that is significantly associated with the stated response against likelihood of availing or offering walk-sharing. The one-way ANOVA test showed significant results only for the 'existing mode of travel' variable. Tukey's Test, which allows for pairwise comparisons between the means of each group, was conducted where the only statistically significant difference between means (at 95% CI) was found between the 'walk only' and 'private motorised' group. For the independent samples t-test, the responses were divided into two independent samples, one group of people who used private modes of transport such as a car or motorbike or bike to travel to their most commonly visited supermarket, and the other group who availed either public transport or taxi, or simply walked to their nearest supermarket. It was found that the mean likelihood score (on the Likert scale of 0 to 4) to avail walk-sharing, was significantly higher (at 99% Confidence Interval) for the respondents whose existing mode of travel was either public transport, a cab or simply walking. This means that people who do not usually use their private vehicle, are more likely to avail walk-sharing. On the other hand, people who travel using their private vehicles, are less willing to switch to walk-sharing as travel mode.

These results can be supported by findings from existing studies which suggest that people who drive more often have lower distance thresholds for walk trips, and consequently walk less (Fairnie, Wilby, and Saunders, 2016; Ralph et al., 2020). Eady and Burtt (2019) had shown that adults without a driving license in Victoria, Australia were more likely to walk (33%) than those with a full licence (26%). The distribution of responses for these two groups are shown in Figure 19.

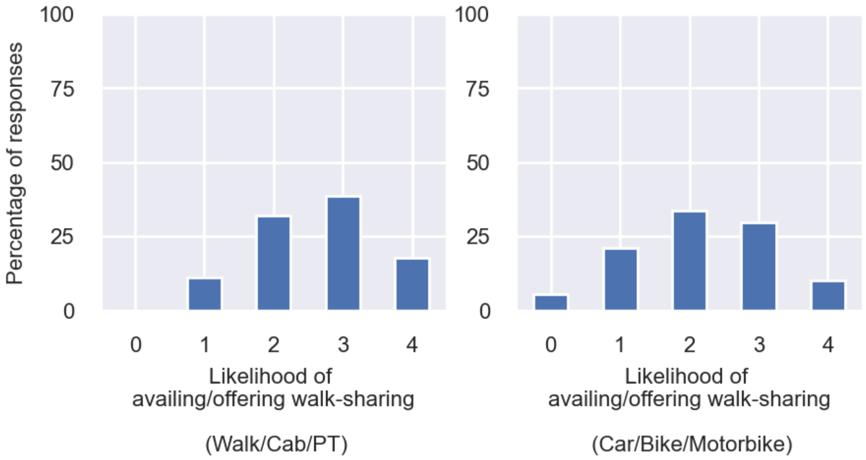

Figure 19: Distribution of responses on the Likert scale by existing mode of travel (0 = Highly unlikely, 4 = Highly likely)

5.5 CONCLUSIONS

Earlier, Chapter 3 had outlined the theoretical framework of walk-sharing and Chapter 4 had proved its technical viability. But, it fell short in terms of not considering public acceptance and feedback about walk-sharing. An online questionnaire survey was conducted to collect information about public perception on walk-sharing. This chapter presented a summary of the responses obtained from conducting the survey and presented the key findings derived from analysing these results.

The survey collected responses from 234 people residing in Australia at the time of the survey, asking them questions regarding their socio-demographic information, travel habits and probable preferences related to walk-sharing. The survey had illustrated the distributions of waiting time and detour time preferences of the respondents. In terms of waiting time, the survey found that while majority of the people were willing to wait up to 10 minutes for matchmaking, there was also a significant portion who were more flexible, and were willing to wait more than 15 minutes. In terms of detour, most people preferred to limit their detour time within 5 minutes. Association of these results with socio-demographics led to the finding that respondents born in Australia were more flexible in terms of waiting time threshold, although similar evidence in the literature was absent.

In terms of social preference, it was found that women mostly preferred walking companion of the same gender, as opposed to men, who are more flexible in terms of the gender preference. This was backed up by sufficient evidence in relevant literature. In terms of likelihood to participate in walk-sharing, people were more inclined to offer walk-sharing (participating for people who need it) as compared to avail walk-sharing (themselves feeling the need for walk-sharing). Overall, the response of the survey participants were positive towards walk-sharing. It was also observed that the likelihood of availing or offering walk-sharing was significantly associated with the respondents' *existing mode of travel*. People who use public transport, a cab, or simply walk to their destination, are more likely to avail walk-sharing in a similar setting, as compared to people using private vehicles for their journeys.

Given that walk-sharing is a novel intervention and a new form of shared mobility, the survey was the first of its kind. Therefore, the survey provided novel and valuable insights and will be of interest to the scientific community. The stated preferences of the respondents gave deeper insights into the general distribution of spatio-temporal and social preference thresholds, the general likelihood of participating in walk-sharing, and their association with the socio-demographics and travel behaviour of the respondents. However, the motivation for conducting the survey was not limited to the mere presentation of these findings. Chapter 6 shows how these findings were incorporated into the calibration procedure of the developed base walk-sharing model, to understand the practical effectiveness of walk-sharing in terms of pedestrian safety and safety perception improvement, and whether walk-sharing can be practically viable in a real-world scenario.

6

INVESTIGATING THE PRACTICAL EFFECTIVENESS OF WALK-SHARING

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*This chapter is based on the manuscript "**Investigating the practical viability of walk-sharing in improving pedestrian safety**" published in* Computational Urban Science *by Bhowmick, Winter, Stevenson and Vortisch (2021). My contribution as the first author of this manuscript includes proposing the hypothesis and the research problem, designing a systematic literature review method, design and implementation of research methods, analysing the results and presenting the discussion and conclusions. These works were supervised by Prof. Stephan Winter (my primary supervisor at The University of Melbourne), Prof. Mark Stevenson (my co-supervisor at The University of Melbourne), and Prof. Peter Vortisch (my primary supervisor at Karlsruhe Institute of Technology) who provided feedback and suggestions at every stage of this study.*

Earlier, in Chapter 4, it was shown how the performance of walk-sharing varied under differing levels of critical factors using synthetic data. Consequently, real-world mobility data was fed into the base walk-sharing model to establish the technical viability of walk-sharing. There, generalised assumptions were made with regards to the spatio-temporal preferences of the pedestrian agents in the model, without the provision of multi-class agents and social preferences. In Chapter 5, actual community preferences were revealed with the help of a questionnaire survey. This chapter aims to incorporate the findings from the survey into the base walk-sharing model, thereby calibrating it. The modified, calibrated model includes multiple classes of agents to introduce heterogeneity, and accommodates not only actual spatio-temporal, but also social preferences of people. Hence, this chapter evaluates walk-sharing in a more realistic context, thereby aiming to deduce its practical effectiveness in improving pedestrian safety and safety perception, and consequently, practical viability in a real-world scenario.

6.1 RESEARCH QUESTION

This chapter aims to answer the following research question.

- To what extent can walk-sharing practically improve pedestrian safety and safety perception in a real-world urban scenario?

Safety perception is subjective, and therefore challenging to measure objectively. As stated in Chapter 4, safety and safety perception improvement will be measured by the introduced proxy measure, *safety index*.

6.2 MODEL CALIBRATION FOR UNIVERSITY SCENARIO

This section explains, in detail, the calibration process of the base walk-sharing model (presented in Chapter 4) based on the evidence obtained from the results of the survey on stated preferences of people related to walk-sharing (presented in Chapter 5). The following sections of this chapter discuss the suitability of testing walk-sharing in a university scenario, the campus Wi-Fi dataset used for the simulations, the existing walk-sharing model in brief, the revised parameter thresholds based on the survey responses, and the modification of the matching algorithm inside the walk-sharing model.

6.2.1 *Suitability of walk-sharing for university campuses*

While a university campus may seem apparently safer than the streets surrounding it, this perception could be argued against on multiple fronts. First, many public university campuses are not gated, so access and egress to the outdoor areas of the campus is seamless. Second, even if the campus has stricter access controls, students or staff walking to public transport stops must traverse a significant portion of their trip outside the campus. Third, there have been safety issues raised consistently, even inside university campuses. Hence, both actual and perceived risk does not always vary significantly across the geographical boundaries of the campus. Walk-sharing seems suitable for such a scenario. University campuses and surrounding areas are more walkable in general. They usually cater to numerous pedestrian trips, because walking is the first leg of most journeys. So sufficient pedestrian demand and relative spatial proximity between people inside a university campus, clubbed with existing safety challenges, make university campus a favourable location (or scenario) where walk-sharing could be both practically viable and effective in terms of perceived and actual risk reduction.

6.2.2 *Campus Wi-Fi data*

The University of Melbourne collects data about devices accessing their on-campus Wi-Fi network for the purpose of space management. In the event of a device accessing (probing) the university's Wi-Fi network, the details of this action are recorded along with relevant data. This information is securely retained in the university's database. We had obtained a completely anonymised dataset from the university containing the last probing event of every device every day. These include devices used by staff and students inside the Parkville campus of the university for every day of the year 2019. The dataset contains 12.14 million records for the calendar year of 2019. This amounts to approximately 34k *last seen* records per day with 208,667 unique devices probing throughout 2019. The spatial granularity was at the building level while the temporal granularity was at the minute level.

Necessary preprocessing steps were conducted to deduce the number of people from the number of devices, so that these daily *last seen* records can act as an appropriate proxy data for people exiting the campus from different buildings at different times of the day. Due to privacy concerns, access to the personal level data was not granted by the dataset providers, and hence identifying multiple records resulting from a single person was challenging by ourselves. As per our request, a preliminary analysis was conducted by the dataset providers at the university to estimate the average device-to-person ratio for the entire dataset, given their access to privacy-sensitive personal data as well. Static devices were first filtered out by the dataset providers, as well as probing events to outdoor Wi-Fi receivers. Since people usually carry more than one device with themselves that is connected to the Wi-Fi network (e. g., a smartphone and a laptop), some analysis was necessary to estimate the number of people from the number of probing events. They arrived at an average value of 1.8 devices per person. Hence, 45% of the records for any given hour of a given day were removed randomly (based on the obtained ratio of 1.8 devices per person) before conducting the simulation.

For the simulations, the previously selected three days in Chapter 4 viz., 2^{nd} February, 21^{st} November and 11^{th} April. The choices are such as they correspond to the $5^{th} percentile$, $50^{th} percentile$ and $95^{th} percentile$ of daily exit record counts, respectively. Data on the pedestrian network surrounding the university campus was obtained using OpenStreetMap. The network has been illustrated in Figure 20.

Figure 20: Pedestrian network in and around Parkville campus of University of Melbourne; green squares = tram stops, orange squares = bus stops

6.2.3 *Modified parameter thresholds*

In Chapter 4, it was assumed that all the agents in the study are willing to participate in the walk-sharing scheme, since there was limited information on how people will perceive walk-sharing. Realistically, there will be a proportion of people who would not be willing to participate in walk-sharing, even if it satisfies their space-time and social constraints. To accommodate for this proportion of the population, *Initial Acceptance Rate (IAR)* has been defined. IAR is the proportion of agents from a population who are willing to participate in walk-sharing, provided it satisfies their space-time and social constraints. The rest of the agents will not avail it anyway.

Based on the analysis presented in Section 5.4.3, that the likelihood of availing or offering walk-sharing is strongly associated with the existing travel mode, the agents were divided into two separate classes. From the responses received through our survey, 34 out of 53 full-time students (64%) and 77 out of 142 part-time and full-time workers (54%) said that they either walk or avail public transport for commute. As per the 2019 Annual Report of The University of Melbourne, 9380 (14%) staff were employed with the student load standing at 54714 (86%). The survey percentages were multiplied with the university's numbers to obtain the share of agents who walk to their destination or avail public transport. That estimate comes to approximately 63% (64% of 86 added with 54% of 14). Given that the university campus holds ample walkable spaces and transit services around it, the number of people walking will be higher than the general population, as represented by the survey. Therefore, the share was increased from 63% to 70%. In summary, it was assumed (backed by proxy evidence) that 70% walk to their nearest public transport stop while 30% of the agents use their personal vehicle, either a car or a bike.

Given the responses on the Likert scale appear to be normally distributed, the mean likelihood score for the two classes were calculated. For the first class of agents who walk to avail public transport, the calculated mean likelihood score is 2.63 with a standard deviation of 0.9 (walking only and public transport users from the survey). For the second class of agents who use their personal vehicles, the calculated mean likelihood score is 2.18 with a standard deviation of 1.05. Based on these statistics, a likelihood score was assigned to each agent. Then, IAR was calculated by counting the proportion of agents across both classes whose assigned likelihood score was 3.0 or more. This meant that agents who are either *Likely* or *Highly likely* (based on point 3 and point 4 respectively on the Likert scale) to participate in walk-sharing, were considered to be part of the new walk-sharing model. Consequently, pedestrian demand for walk-sharing reduced to roughly 30% of the demand that was used in the base walk-sharing model. This can be observed from Figure 21. The rest of the agents were discarded from the simulation.

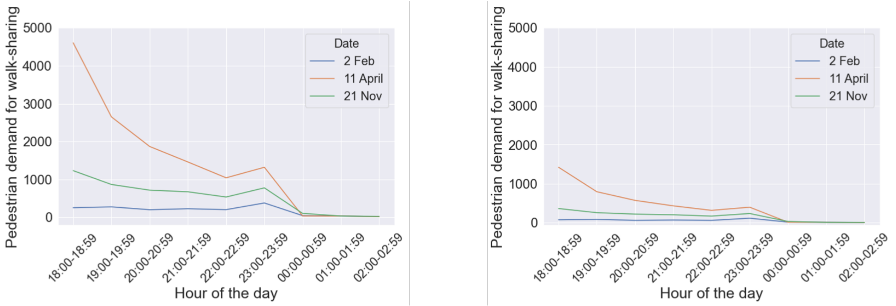

Figure 21: Number of agents willing to avail walk-sharing, before introducing IAR (left) and after IAR (right).

For the maximum waiting time threshold, it was observed that the distributions were significantly contrasting when split using *place of birth*. It was found that the respondents born in Australia were temporally more flexible as compared to the ones born outside Australia. However, it was challenging to support this finding with established evidence, given its non-trivial nature and the socio-demographic diversity within the migrant population in Australia. Relevant literature, mostly involving ridesharing, were reviewed, but similar findings could not be found. Instead of speculation, the maximum waiting time distribution obtained from the survey was replicated using a log-normal distribution up to 15 minutes. The observed mean (6 minutes) and standard deviation (4 minutes) from the survey was used. Since 30% of respondents had stated their willingness to wait more than 15 minutes, a separate class of agents were introduced, whose maximum waiting time varied uniformly within the range of 16-20 minutes.

From the set of responses, a mean detour time threshold preference of 6 minutes was calculated, which is equivalent to 432 m detour length, assuming a mean walking speed of 1.2 m/s (VicRoads, 2019). The best proxy variable for detour length in the walk-sharing model is *distance to buddy threshold*. Using data from 21st November (50th percentile demand day), the variation in mean detour length (mean calculated over 6 PM in the evening to 3 AM in the morning) versus distance to buddy threshold was simulated. Using the results shown in Figure 22, it was observed that a peak detour length of 331 m corresponded to the distance to buddy threshold of 700 m. 331 m is equivalent to a detour time of roughly 5 minutes which is close to 6 minutes, the approximate mean value obtained from the survey. Hence, the distance to buddy threshold of the modified model was set at 700 m.

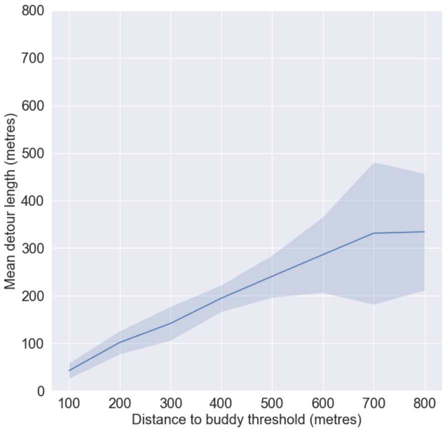

Figure 22: Detour length vs distance to buddy threshold for 21st November; mean calculated over 6 PM in the evening to 3 AM in the morning, 2 standard deviations shown.

As per the 2019 Annual Report of The University of Melbourne, the percentage of female student enrolments was approximately 57% while the share of women staff was also 57%. Gender classification was binary (Male and Female), given that only two respondents out of 234 identified themselves as non-binary. Given that the representation of the non-binary gender was insignificant, the gender classification of the agents in the model was limited to a binary one (either male or female). Hence, the assigned probability of an agent being a female was set at 0.57, while that of being a male was set at 0.43. The parameter thresholds set for the calibrated model are summarised as follows:

- Existing modes of travel for agents (influencing IAR):
  - Walking to PT stop = 70%
  - Car and bike = 30%
- Maximum waiting time
  - Normal agents = $\ln\left(\text{lognormal}\left(6\,min, 4\,min\right)\right)$
  - Flexible agents = $\text{uniform}\left(15\,min - 20\,min\right)$
- Distance to buddy threshold = 700 m
- Distance to destination threshold = 700 m
- Gender
  - Male = 43%

  - Female = 57%
- Same gender preference probability
  - Male = 0.1 (10% of male agents prefer only male agents)
  - Female = 0.5 (50% of female agents prefer only female agents)

The comparison between the parameter thresholds of the base model developed in Chapter 4 and the calibrated model is illustrated in Table 2.

Parameter	Value in initial model	Value in calibrated model
Maximum waiting time	Uniformly varied between 5-10 min	Normal agents = ln (lognormal (6 min, 4 min)) Flexible agents = uniform (15 min - 20 min)
Distance to buddy threshold	200 m	700 m
Distance to destination threshold	700 m	700 m
Existing travel modes	NA	Walking to PT stop = 70% Car and bike = 30%
Gender	NA	Male agents = 43% Female agents = 57%
Same gender preference probability	NA	Male agents = 0.1 Female agents = 0.5

Table 2: Comparison of parameter thresholds between the initial model developed in the previous study and the calibrated model.

6.2.4 *Modified matching algorithm*

The matching algorithm has been modified to accommodate for the gender preference of the agents. In the base model, any agent could be matched with any other agent given they satisfied some spatio-temporal constraints, such as distance to buddy threshold or maximum waiting time. In this instance, there is presence of sufficient evidence regarding social preference of people, with almost half of the female respondents stating that they prefer a walking companion of the same gender. This same-gender preference is substantially lower, only 10% in the case of male respondents. Gender preference was randomly assigned to all agents, with all female agents having a 50% chance of having same-gender preference, and male agents having a 10% chance. In the matching step, agents having same-gender preference can only be assigned to another agent of the same gender. Hence, while constructing the distance (impedance) matrix, it was checked whether the two agents in question are of the same gender. If not, a check is made to see whether either one of them have a same-gender only preference. If that is the case, then to nullify the chances of a match, the corresponding impedance value in the matrix is replaced with a large positive value. This modification is stated between Line 6 - Line 17 in Algorithm 3. The rest of the algorithm remains the same as mentioned in Chapter 4.

Algorithm 3 Modified matching algorithm.

```
Require: System is characterised by
    • system time ← $t$
    • time step ← $t_{step}$
    • Matching pool at time t ← $MP_{D,t}$
    • Distance matrix at time t ← $Mat_{D,t}$
    • List of matched agents ← $L_{matched}$
  Pedestrian agents $P_i$ where each agent is characterised by
    • Starting time ← $T_{start}$
    • Waiting time threshold ← $WT_{max}$
    • Matching distance threshold ← $D_{th}$
    • Gender ← $G$
    • Gender preference ← $G_{pref}$ (Same gender only = 0, No
      preference = 1)

for all $P_i \in P$ do                                   ▷ Fill matching pool
    if $t = T_{start,P_i}$ then
        add $P_i$ to $MP_{D,t}$
    end if
end for

for all $P_i \in P$ and $P_j \in P$ do ▷ Construct distance/impedance matrix
    if $G_i = G_j$ then
        $D_{P_i,P_j} \leftarrow dist(P_i, P_j)$
    else
        if $G_{pref,i} = 0$ or $G_{pref,j} = 0$ then
            $D_{P_i,P_j} \leftarrow largepositivevalue$
        else
            $D_{P_i,P_j} \leftarrow dist(P_i, P_j)$
        end if
    end if
end for
Elements on the diagonal and above the diagonal
← $largepositivevalue$
```

....continued on the next page

....continued from the previous page

```
$D_{min} \leftarrow min(Mat_{D,t})$                                ▷ Start matching agents
while $D_{min} \leqslant D_{th}$ do
    for all elements in $Mat_{D,t}$ do
        if $D_{P_i,P_j} = D_{min}$ then
            if $L_{matched}$ contains $P_i$ or $P_j$ then
                do nothing
            else
                $L_{matched} \leftarrow L_{matched} + [P_i, P_j]$
                $D_{ij} \leftarrow largepositivevalue$
            end if
        end if
    end for
    $D_{min} \leftarrow min(Mat_{D,t})$
end while

if $L_{matched}$ contains $P_i$ then            ▷ Agent removal from matching pool
    remove $P_i$ from $MP_{D,t}$
else
    $WT_{P_i} \leftarrow t - T_{start,P_i}$
end if
if $WT_{P_i} \geqslant WT_{max,P_i}$ then
    remove $P_i$ from $MP_{D,t}$
end if

$t \leftarrow t + t_{step}$                                        ▷ Move to the next time state
```

6.3 RESULTS

Integrating the Wi-Fi data into the calibrated agent-based walk-sharing model, ensuring the parameter thresholds had been adjusted to take account of the survey results, the simulations were executed for each scenario. Stochasticity due to the randomness involved in temporal and social preference assignment to the agents was mitigated by conducting repetitive simulation runs, and consequently taking the average. Comparisons for each of the performance metrics, viz., waiting time, walk alone length, detour length, matching rate and finally, safety index are presented in the following sections.

6.3.1 *Waiting time*

It can be observed in Figure 23 that mean waiting time per person has reduced considerably in the results obtained from the calibrated model, as compared to the results from the base model. The mean is taken over all agents present in the system, irrespective of the fact whether they were matched or not. This can be primarily attributed to the fact that *distance to buddy threshold* has been increased from 200 m to 700 m, given that respondents had stated that they are more flexible in terms of detour distance. It was observed in Chapter 4 that waiting time per person increased with lower pedestrian demand but reduced with higher values of distance to buddy threshold. While demand has been substantially low, it was still enough to not increase waiting time significantly, while the fact that *distance to buddy threshold* was increased from 200 m to 700 m had a greater weight and eventually resulted in significantly lower waiting times. Till midnight, waiting time remains well below 5 minutes, and after that it ranges from 5 minutes to 10 minutes. These are acceptable values, given that the stated responses from the survey exhibited a mean of 10 minutes as the maximum preferred waiting time (see Figure 13).

6.3.2 *Walk alone length and detour length*

The calibrated model exhibits significantly higher values of walk alone length and detour length when compared to the base model. This occurs due to two reasons. First, *distance to buddy threshold* has been

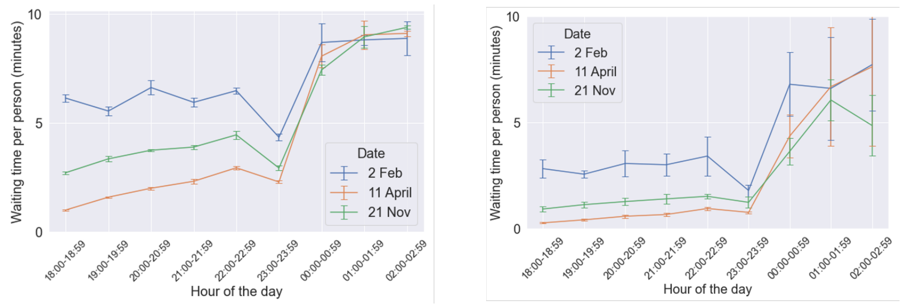

Figure 23: Results of mean waiting time per person (one standard deviation error bars shows) from the initial model (left) and the calibrated model (right).

increased from 200 m to 700 m in the calibrated model as per the responses received from the survey. So people are more flexible (than initially assumed) to be matched with potential companions who are farther away. It was observed in the sensitivity analysis of Chapter 4 that distance to buddy threshold has a substantial impact on both detour length and walk alone length. Hence, it is the major reason behind the significant rise in these two performance metrics. Second, the incorporation of same-gender preference in the agents has resulted in many nearby matches being rendered invalid (cases where two agents belonged to different genders), and thus forced the model to consider matches farther away. Yet, both walk alone length and detour length remain in the range of roughly 400 m, corresponding to less than 6 minutes of walk alone time or detour time. It was observed from the responses in the survey that the mean detour time was roughly a little over 6 minutes (see Figure 13). Hence, while both walk alone length and detour length have increased thereby reducing performance, still they remain within the acceptable thresholds stated by the community.

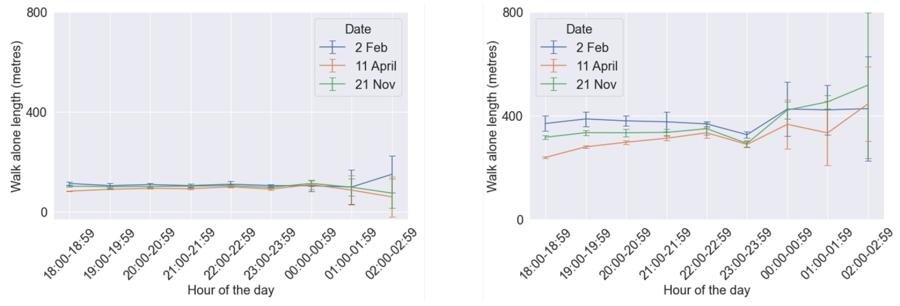

Figure 24: Results of mean walk alone length per person (one standard deviation error bars shows) from the initial model (left) and the calibrated model (right).

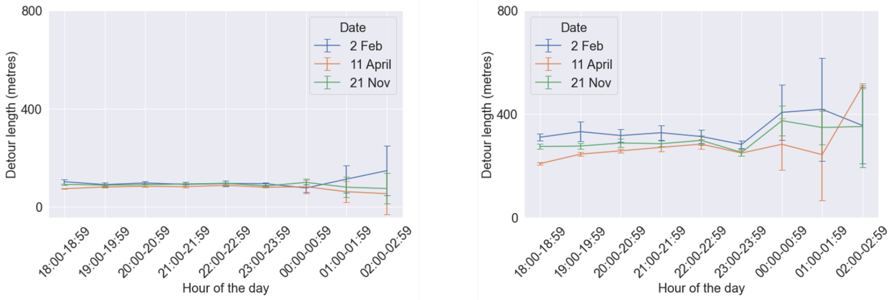

Figure 25: Results of mean detour length per person (one standard deviation error bars shows) from the initial model (left) and the calibrated model (right).

6.3.3 *Matching rate*

Matching rates have improved in the calibrated model as can be observed from Figure 26. This is more significant for 2nd February which corresponds to the 5th percentile demand day. For this day, in the base model, matching rate varied between 40-60% before midnight, whereas in the calibrated model, matching rate stays well above 60%. Earlier in Chapter 4, it was observed that matching rate decreases with a reduction in demand. Also, matching rate reduces due to incorporation of social preferences, which makes the number of suitable matches fewer. But, the significant increase in matching rate is due to an increase in distance to buddy threshold. This is in line with our earlier observations in Chapter 4, where an increase in distance to buddy threshold lead to sharp improvements in matching rate, even in low-demand scenarios.

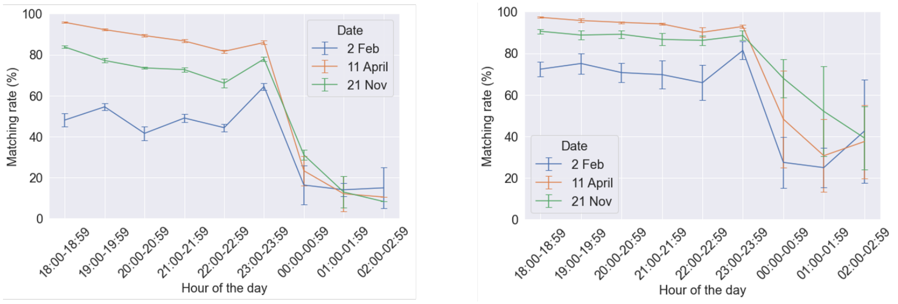

Figure 26: Results of system matching rate (one standard deviation error bars shows) from the initial model (left) and the calibrated model (right).

6.3.4 *Safety index*

In Chapter 4, *safety index* was defined as the "*mean walk alone length saved per capita expressed as a percentage of the distance walked by a person in the absence of walk-sharing*". Safety index acts as a proxy for objectively measuring the extent of safety improvement done by walk-sharing. It can be observed in Figure 27 that the safety index values before midnight has declined slightly, when compared to results from our initial model. This is a resultant of increased distance walked alone by the agents, due to greater spatio-temporal flexibility. Considering the 21^{st} November which corresponds to the 50^{th} percentile pedestrian demand, the safety index varies between 40-50% before midnight, a reduction from 60-70%. This means that for half of the days, walk-sharing can contribute towards 50% improvement of pedestrian safety perception and thus reduced fear of crime while walking.

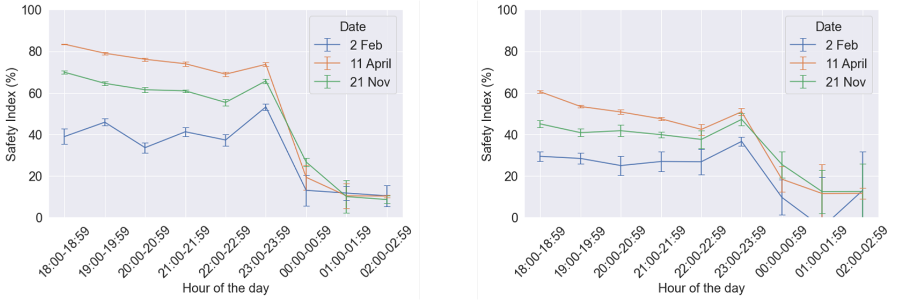

Figure 27: Results of safety index (one standard deviation error bars shows) from the initial model (left) and the calibrated model (right).

6.4 DISCUSSION

The results obtained from the calibrated model, where the parameter selection was more informed, shows that walk-sharing has the ability to make a significant improvement in pedestrian safety perception levels in a real-world scenario, while exhibiting acceptable values of other performance metrics, as per the results from the survey presented in Chapter 5. This finding is in line with the results from Chapter 4, where a possible maximum value of walk-sharing's capacity to improve pedestrian safety was stated. It was expected, that after calibration, the performance of walk-sharing will reduce. While the performance has reduced in terms of walk alone length, detour length and safety index, significant improvements were also seen in terms of waiting time and matching rate. Both waiting time and detour time remained within the preferred thresholds of the survey respondents, which could improve the appeal of walk-sharing. It must be noted that the performance of walk-sharing diminished significantly in the face of lower pedestrian demand levels in the base model. With the inception of Initial Acceptance Rate, the pedestrian demand had reduced to 30% of the magnitude of our previous model. Apart from that, the incorporation of social preference, viz., the same-gender preference criteria, rendered many matches invalid, many of which were perfectly acceptable in the base model. While these have driven down the performance of walk-sharing on one hand, what boosted its performance on the other was the increased spatio-temporal flexibility of people, which was underestimated previously, in terms of distance to buddy threshold, and greater distribution of waiting time threshold, now ranging up to 20 minutes. Overall, it can be observed that in spite of the matching complexities introduced, walk-sharing is able to establish its practical viability to improve safety perception and safety of pedestrians.

6.5 CONCLUSIONS

With increased fear of crime among pedestrians, walk-sharing provides an alternative intervention that promises significant improvements in the urban walking experience. Walk-sharing aims to reduce fear of crime and thereby enhance pedestrian safety and safety perception. Walk-sharing has its distinct advantages over its traditional counterparts, given that it is more inexpensive, less data-dependent, holistic and scalable. While Chapter 3 had outlined the theoretical framework of walk-sharing and Chapter 4 had proved its technical viability, they fell short in terms of not considering public acceptance and feedback about the same. To plug this research gap, a web-based survey was conducted to understand public perception on walk-sharing, which was discussed in Chapter 5.

Given that public perception on walk-sharing was never studied before, these results of the survey were interesting. Nevertheless, the objective this thesis, and more specifically this chapter, was not limited to the mere presentation of survey results. The plan was to incorporate these findings in to the base walk-sharing model (presented in Chapter 4) and calibrate it to understand whether walk-sharing can be practically viable in a real-world scenario. The calibrated walk-sharing model delivered promising results even under significantly low pedestrian demand levels and more complex matching circumstances. Walk-sharing alone is still able to improve pedestrian safety in the range of 20-60% (more than 40% for half of the days) in the university scenario. It achieves these figures keeping other performance metrics such as matching rate, waiting time, walk alone length and detour length under acceptable thresholds. In an age of ubiquitous computing, IoT, efficient location-based services and smartphones, walk-sharing could be the smarter solution that brings people back to the sidewalks, promote walking as not only a healthier mobility choice but a safe one as well, and consequently progress towards more sustainable urban living, by reducing short-distance motorised traffic.

Representative assumptions were made choosing parameter values in the more realistic simulation in Chapter 4. However, in this chapter, these parameters were calibrated based on evidence obtained from the survey. This was necessary as the calibration of parameters via the survey produces grounded results (based on evidence rather than representative assumptions). However, this does not render the university scenario simulation in Chapter 4 as redundant. The uncalibrated simulation acts as a baseline scenario as it allows for comparison between the results of the uncalibrated (assumption-based) and calibrated simulation (evidence-based), thereby showing the impact of parameter calibration on the performance of walk-sharing in a real-world setting. Furthermore, the logical flow of works undertaken by the author is more transparent in this manner, allowing for smoother reading of the thesis. Therefore, there lies significance of testing the technical viability of walk-sharing in a university scenario as was conducted in Chapter 4.

7

DISCUSSION AND CONCLUSIONS

Walking, as an active travel mode, has a host of individual and public health benefits. Additionally, more frequent walking for transport means less reliance on private motorised vehicles, which in turn leads to lesser emissions, lesser congestion and therefore, more liveable urban communities. Understandably, walking is not always convenient. For example, walking for long commute distances, or walking under adverse weather conditions are not popular travel choices. In such situations, people would avail alternative modes that make their travel more convenient. But, even when walking is a convenient choice for transport e. g., short trip to the nearest supermarket, or to the nearest train station, people do not always choose to walk. Under critical circumstances, such as after-dark hours, or trips through sparsely populated land-uses, the major deterrent for walking is the fear of crime. With pedestrians feeling vulnerable outdoors at critical times of the day, the appeal of outdoor walking has reduced significantly, with people switching to costlier alternatives, or not walking at all.

Existing methods aimed at improving the safety perception of pedestrians are not the most efficient, let alone effective. Approaches such as modifications in urban design, or installation of street furniture aimed at improving walkability and reduced fear of places (Day, Anderson, Powe, McMillan, and Winn, 2007; Ferrer, Ruiz, and Mars, 2015; Fisher and Nasar, 1992; Fotios and Castleton, 2016; Painter, 1994) are costly, time-consuming, involve rigorous planning and substantial human effort. With the advent of smartphones and consequently, efficient location-based services, more recent IT approaches such as crowdsourcing knowledge about fear of places, safe route recommendation systems backed up by proxy data sources (Fu, Lu, and Lu, 2014; Kim, Cha, and Sandholm, 2014; Utamima and Djunaidy, 2017), have gained prominence. But these reactive approaches significantly rely on the availability of data that can act as a reliable proxy for fear of places, making them less scaleable and transferable. Furthermore, similar approaches have been discarded by the public owing to their non-inclusive nature and consequent profiling of racial and socio-economic groups (Dewey, 2014; Greenfield, 2013).

With increased fear of crime among pedestrians, walk-sharing provides a smarter intervention that bypasses the drawbacks of the existing approaches, while promising significant improvements in the urban walking experience. Given fear of crime is positively associated with walking alone (Badger, 2014; Roberts, 2014; Sacco, 1984), walk-sharing exploits the spatio-temporal proximity of people, helping them walk in company as compared to walking alone, thereby minimising fear of places and consequently enhancing pedestrian safety and safety perception (Clifton and Livi, 2005; Cohen and Felson, 1979; Iglesias, Greene, and Dios Ortúzar, 2013; Painter, 1994). Walk-sharing has its distinct advantages over the existing approaches, given that it is more inexpensive, less data-dependent, holistic and scaleable.

The central hypothesis of this thesis was that **walk-sharing can serve a significant portion of the community by significantly improving the safety and safety perception of pedestrians, thereby elevating the attractiveness of walking (encouraging people to walk when viable without personal safety concerns) even at critical times of the day (hours when pedestrians feel vulnerable and prefer a companion to walk with), with acceptable levels of costs (ones that are critical in walk-sharing).** This thesis establishes this hypothesis in multiple stages, using agent-based modelling techniques fed with real-world mobility data and responses from the community about their preferences on walk-sharing.

- This thesis proposes the novel concept of walk-sharing, presents its technical framework and conceptual model, and discusses the theoretical foundations of walk-sharing by outlining the costs and factors that are critical to the performance of walk-sharing (Chapter 3).
- To understand the sensitivity of walk-sharing and objectively measure the performance of walk-sharing under plausible scenarios, this thesis presents the materialisation of the proposed conceptual model into an agent-based simulation model of walk-sharing. This base walk-sharing model is fed with synthetic data to obtain expected sensitivity trends, thereby establishing proof of concept. Additionally, using real-world mobility data with justified assumptions with respect to spatio-temporal parameter

thresholds in the agent-based model, the technical (theoretical) viability of walk-sharing is tested (Chapter 4).

- To understand the public perceptions on walk-sharing, a survey was conducted, the results of which were presented in this thesis (Chapter 5).
- These results were consequently incorporated into the model to calibrate it, and the calibrated model, with informed parameter choices of spatio-temporal and social preferences of people, was run in a university campus scenario to establish practical viability of walk-sharing. The results exhibited that walk-sharing has the capacity to make a significant improvement in pedestrian safety perception levels in the university campus scenario, while resulting in acceptable values of other performance metrics in terms of the thresholds obtained from the survey (Chapter 6).

This chapter discusses the major findings of this thesis with respect to the hypotheses and research questions stated in Chapter 1. It further highlights the key scientific contributions of this thesis. The chapter concludes by discussing the possible research avenues based on this thesis, that can be explored in future.

7.1 SUMMARY OF FINDINGS

This section summarises the results of the previous chapters of this thesis, discusses the key findings in relation to answering the stated research questions.

7.1.1 *Introduction of walk-sharing*

The first objective of this thesis was to present a novel intervention that can mitigate fear of crime among pedestrian in outdoor urban spaces. In this regard, this thesis presented walk-sharing, a smarter way to improve the uptake of walking by making people walk together, and thereby improve safety and safety perception. Chapter 3 discussed the concept of walk-sharing and how it aims to combat the challenge of improving safety and safety perception of pedestrians, and presented the major conceptual distinctions between walk-sharing and other existing shared forms of mobility, thereby arguing the necessity to pursue with the investigation of viability of walk-sharing.

In response to the first research question of Chapter 3 viz., "**How can a walk-sharing system be designed?**", a simple technical framework of walk-sharing in space was presented, along with a design of the proposed walk-sharing system in the form of a conceptual model, projecting an abstract idea of how the mechanism of walk-sharing could be designed in the real-world.

In response to the second research question of Chapter 3 viz., "**While the benefits of walk-sharing are apparent, what are the possible deterrents (costs) of walk-sharing?**", the costs of walk-sharing viz., *waiting time*, *walk alone length*, *detour length* along with *matching rate* were identified and defined. These represent performance metrics of walk-sharing which had helped in objectively measuring the performance of walk-sharing in plausible scenarios. In response to the final research question of Chapter 3 viz., "**What are the factors that will be critical to the performance of walk-sharing?**", the relevant critical spatio-temporal factors identified were *pedestrian demand*, *distance to buddy threshold*, *distance to destination threshold* and *maximum waiting time threshold* which would subsequently serve as the independent parameters incorporated in the agent-based walk-sharing simulation model.

7.1.2 *Walk-sharing model*

Chapter 4 discussed the materialisation of the conceptual model of walk-sharing presented in Chapter 3 into an agent-based model. This was done to objectively measure the performance of walk-sharing under multiple plausible scenarios via simulations, with varying levels of spatio-temporal factors critical to its performance. For the realisation of the conceptual model into an agent-based model, a walk-sharing algorithm and a matching algorithm were developed and implemented in the agent-based modelling platform GAMA.

In response to the first research question of Chapter 4 viz., "**How sensitive are the costs of walk-sharing to varying levels of pedestrian demand and other critical factors representing spatio-temporal preferences of pedestrians?**", the base walk-sharing model was fed with synthetic pedestrian road network data (regular grid-shaped network structure) and synthetic population data (randomly distributed across network nodes with uniform probability distribution across space). The relevant critical factors identified in Chapter 3 were used as explanatory parameters in the walk-sharing model. Levels of these critical factors were varied in the simulations, creating synthetic, yet plausible scenarios. Consequently, the following outcomes were obtained which served to answer the aforementioned research question.

- *Pedestrian demand* was found to be positively correlated with the performance of walk-sharing. With greater demand levels, system matching rate improved substantially, while average waiting time reduced, with walk alone length and detour remaining fairly constant.
- *Distance to buddy threshold* had a mixed relationship with the performance of walk-sharing. Across different demand levels, with an increase in distance to buddy threshold, waiting time reduced significantly, while matching rate increased substantially. But, both detour length and walk alone length increased significantly, given the matches were quicker, but farther away.
- *Distance to destination threshold* was consistently inversely correlated with the performance of the walk-sharing model. With its increasing levels, average waiting time, walk alone length and detour length increased, while system matching rate dropped significantly.
- *Maximum waiting time threshold* also had mixed impacts on the performance of walk-sharing. Understandably, average waiting time increased with an increase in maximum waiting time levels, but matching rate improved substantially. Detour length and walk alone length remained fairly constant, as they are mostly dependent on spatial flexibility as compared to temporal flexibility of the agents.

7.1.3 *Technical viability of walk-sharing*

The final research question of Chapter 4 viz., "**Is it technically viable to implement walk-sharing in a real-world scenario?**" was answered by using campus exit count data of staff and students into the walk-sharing simulation model. Walk-sharing produced apparently acceptable values of performance metrics (and hence, technically viable) till midnight, especially for the median and high exit count scenarios. For at least 50% of the year, walk-sharing was technically viable with minor spatio-temporal costs. Even for the low exit count scenario, walk-sharing was technically viable till midnight. In terms of safety enhancement, it was observed that walk-sharing was able to increase the safety perception of pedestrians by 40 to 80% in almost all cases (more than 60% for half of the time), with the improvement being measured using the percentage of walk alone length it saved.

7.1.4 *Community preferences on walk-sharing*

A web-based questionnaire survey was conducted to collect information about public perception on walk-sharing. Chapter 5 presented a summary of the survey responses and the key findings derived from analysing these responses. The survey received 234 unique responses from people residing in urban and suburban Australia at the time of the survey, asking them questions regarding their socio-demographic information, travel habits and probable preferences related to walk-sharing.

- The first research question of Chapter 5 asked "**What is the likelihood of walk-sharing uptake in the community?**". In terms of likelihood to participate in walk-sharing, people were more inclined to offer walk-sharing (participating for people who need it) as compared to availing walk-sharing (themselves feeling the need for walk-sharing). Overall, the response of the survey participants were positive towards walk-sharing.
- The second research question of Chapter 5 asked "**What is the extent of spatio-temporal compromises that people are willing to make to avail walk-sharing?**". The survey had illustrated the distributions of waiting time and detour time preferences of the respondents. In terms of waiting time, the survey found that while majority of the people were willing to wait up to 10 minutes for matchmaking, there was also a significant portion who were more flexible, and were willing to wait more than 15 minutes. In terms of detour, most people preferred to limit their detour time within 5 minutes.
- The third research question of Chapter 5 asked "**Are there any social preferences related to choice of walking companion**

that may affect the uptake of walk-sharing?". In response to this question, it was found that women mostly preferred walking companion of the same gender, as opposed to men, who are more flexible in terms of the gender preference. This was backed up by sufficient evidence in relevant literature.

- The final research question of Chapter 5 asked "**Do socio-demographic characteristics influence the preferences of people related to walk-sharing?**". In response to this question, it was found that the likelihood of availing or offering walk-sharing was significantly associated with the respondents' *existing mode of travel*. People who use public transport, a cab, or simply walk to their destination, are more likely to avail walk-sharing in a similar setting, as compared to people using private vehicles for their trip. Another significant finding was that respondents born in Australia were more flexible in terms of waiting time threshold, although similar evidence in the literature was absent.

7.1.5 *Practical effectiveness of walk-sharing*

The survey responses were employed to calibrate the base walk-sharing model in Chapter 6. The calibrated model included informed parameter choices of spatio-temporal and social preferences, and localised parameter tuning for the university campus scenario. In response to the research question of this chapter viz., "**To what extent can walk-sharing practically improve pedestrian safety in a real-world urban scenario?**", the key findings were as follows:

- Walk-sharing alone is able to improve pedestrian safety in the range of 20-60% (more than 40% for half of the days) in the university scenario.
- Till midnight, waiting time remains below 5 minutes, while post-midnight, it varies from 5 minutes to 10 minutes. These values are within acceptable thresholds as per the stated responses from the survey which exhibited a mean of 10 minutes as the maximum preferred waiting time.
- Both walk alone length and detour length remain in the range of roughly 200 m to 400 m. 400 m corresponds to less than 6 minutes of walking time. It was observed from the responses in the sur-

vey that the mean detour time was approximately 6 minutes, meaning that the resultant values are within acceptable thresholds.

- The matching rate of the system before midnight remained within 60-90% which is impressive. However, after midnight, matching rate plunges to significantly to lower levels due to dearth in pedestrian demand.

7.2 CRITICAL REFLECTION AND LIMITATIONS

Upon critical reflection of the arguments presented and the methods applied in this thesis to answer the stated research questions, there were certain aspects where this thesis fell short. This section presents a critical discussion of these aspects. These limitations are presented as follows.

7.2.1 *University campus scenario*

The simulations intended to investigate the practical viability of walk-sharing were conducted with mobility data from a university campus. Usually university campuses are more walkable, and involve a substantial number of pedestrian journeys. This makes it more conducive to walk-sharing, as performance of walk-sharing varies significantly with pedestrian demand and the spatio-temporal proximity of pedestrians. In Chapter 6, walk-sharing was found practically viable in the university scenario. But it has not been tested in other, possibly more challenging scenarios. The base model is transferable and can be calibrated as per the requirements of other critical scenarios, given the availability of appropriate mobility data. Also, during modelling, it was assumed that the stated spatio-temporal and social preferences of a person under critical circumstances, is independent of where this circumstance occurs. This means, preferences are assumed to be transferable from scenario to scenario. As per this assumption, the takeaways from the stated preference survey were transferable to the university scenario, and therefore fed unmodified into the model. However, these challenges do not curtail the scientific contributions of this thesis, which has proposed and modelled walk-sharing, and investigated its viability in a real-world scenario.

Although further investigations are data-dependent, the transferability of this walk-sharing model makes estimating viability for specific scenarios possible, via localised calibration of parameters.

7.2.2 *Survey*

To extract community perception on walk-sharing, a web-based questionnaire survey was conducted. Given walk-sharing is at a rudimentary stage of research, stated-preference (SP) method was employed, defining new variables, costs and performance metrics. While SP methods are prone to biased responses, deducing the amount of such bias is challenging, costly and time-consuming and do not fall within the scope of this thesis. Also, the survey was conducted in an online platform due to COVID-19 restrictions, and online survey platforms have their own shortcomings.

The survey was limited to only Australian respondents. This was primarily due to limited funds that could only accommodate the required number of people. Additionally, limiting the respondents to a specific country helped in avoidance of challenges corresponding to socio-economic and cultural diversities across countries governing the preferences related to walk-sharing. Furthermore, there were some trends in the survey that were difficult to explain. For example, it was challenging to explain how a person's place of birth correlates with their spatio-temporal flexibility. Given such findings could not be corroborated from existing literature, they were not incorporated into the calibration process of the walk-sharing model.

The survey was conducted on Amazon Mechanical Turk, and given the rate of response was modest, all the responses were included in the analysis and calibration of the model. Apparently, women were under-represented in the survey (30% compared to the national estimate of 51% (link to census data)). Given that walk-sharing could be predominantly targeted for women, a greater proportion of female respondents would have been ideal. However, this does not affect this study. First, the number of women in the sample were large enough (70 participants) to yield statistically reliable results. Second, gender of the respondent was not found to be significantly influencing their spatio-temporal preferences. The only case where gender was significant, was the preferred gender of their walking companion, as stated in Section 5.4.2.

7.2.3 *Calibration of the walk-sharing model*

Prior to any analysis, it was expected that students would behave differently than staff, meaning that their thresholds relevant to walk-sharing would be different. On the contrary, no such evidence of significant statistical difference in preferred waiting times, detour times or even the likelihood to avail walk-sharing, between students and the working population was found. Hence, relevant generalised distributions obtained from the entire survey sample were applied to the specific agent population (or created agent-classes based on other demographics). For example, waiting times were assigned differently to 'flexible' and 'non-flexible' agents, which is a more generalised demarcation. While parameter tuning more appropriate for the university scenario would have been preferred, the observed findings were not well-aligned with the expected outcomes. Hence, the use of generalised classification is justified for the university scenario as well.

7.2.4 *Proxy measure for safety improvement*

Performance metrics such as *waiting time*, *walk alone length*, *detour length* and *matching rate* are associated with direct measurement of themselves. On the contrary, safety and safety perception are more subjective in nature. Given that the primary objective of walk-sharing is to improve the safety and safety perception of pedestrians, a proxy objective performance metric was necessary to measure the performance of walk-sharing in that regard. Walk-sharing aims to improve safety and safety perception of pedestrians by making them walking in company instead of walking alone. This is based on repeated evidences found in the literature (see Section 2.4) stating that walking alone is the major reason to feel fearful if the environment is capable of making a person fearful.

On that note, this thesis had presented a *safety index*, a performance metric that expressed the *walk alone length saved* as a percentage of the shortest possible route length. As length of walking alone is deducted from pedestrian trips, and given its well-established correlation with feeling fearful under critical circumstances, it has been assumed that an equal proportion of safety and safety perception improvement (equal to the proportion of walk-alone distance reduced) took place.

For example, 50% safety index would reflect a 50% safety and safety perception improvement of pedestrians on an average. But there is an underlying assumption of homogeneity of outdoor urban spaces. This means that safety index ignores spatio-temporal heterogeneity of safety and safety perception in outdoor urban spaces. As the walk-sharing model does not accommodate such spatio-temporal variations, it assumes that people participating in walk-sharing would have feelings of fear along the entire route if they would walk alone. Therefore, the proportion of walk alone length saved is equal to the improvement in safety and safety perception.

In reality, this may not always be true. Only specific portions of a pedestrian's route may encourage feelings of fear, while other locations, such as busy crosswalks or sidewalks on busier roads with more commercial venues, instill sense of safety and security due to greater natural vigilance. Also, at even less busy hours with closed shops and fewer ambient traffic, the entire route may generate only marginally different fear of crime. Thus, walk alone lengths reduced across such a spectrum of outdoor spaces and times, are non-uniform and heterogeneous, something that a non-weighted safety index is unable to represent.

Apparently, this would indicate that the safety index values obtained in Chapter 6 is a more idealistic representation of safety improvement, while more realistic safety improvement values will always be lesser than that. However, it must also be noted that if an entire pedestrian route does not generate fear of crime, the safety index should only be calculated by involving locations where there is fear of crime. If that would be the case, then even if the entire route of a pedestrian participating in walk-sharing is not covered by their companion, safety index could attain a value of 100% (and more interestingly, surpass the achieved levels in Chapter 6), if companionship was present along the portions of the route which generate the feeling of fear. Developing a weighted and more sophisticated metric similar to safety index, which is a function of space-time characteristics of urban road networks, would involve calibration using multiple network and land-use data sources. Also, given safety perception is subjective, both co-companions could have different levels of fear at the same place. Hence, it is extremely challenging to establish a fully robust performance metric, something that needs to be pursued in future. The simpler, non-calibrated safety index presented in this thesis, albeit with certain assumptions, contributes significantly by showing the levels of safety and safety perception improvement possible by implementing walk-sharing.

7.2.5 *Sub-optimal matching heuristic*

The matching algorithm incorporated into the proposed walk-sharing model is based on a simple heuristic and is not optimised, unlike other state-of-the-art optimisation methods found in ridesharing literature. Given that the ridesharing domain has been existing for more than a decade, research in that domain is at a more advanced stage, and researchers now put more emphasis on optimising the matching process by using a range of parameters: meeting points, pooling, anticipated demand, and many more. A similar, more sophisticated, optimised matching algorithm implemented for walk-sharing can easily outperform the sub-optimal heuristic approach presented in this thesis. Since this is the first piece of research on walk-sharing, the primary interest lay in understanding the principle value and the feasibility of walk-sharing, and not on improving the efficiency of an existing scheme or matching process. Even without a more efficient matching algorithm, the proposed walk-sharing scheme performs reasonably well in terms of safety and safety perception improvement and limiting costs within the publicly acceptable thresholds. Hence, a more efficient matching process will only make it perform better, which further strengthens the argument in favour of walk-sharing as an intervention.

7.2.6 *Pedestrian route choice*

The proposed walk-sharing model assumes that all pedestrians walk to their intermediate and final destinations using the shortest available route in terms of route length. While, in reality, pedestrians apply wayfinding heuristics which result in different and usually longer, and never shorter routes. Interestingly, walking along longer heuristic routes would mean walk-sharing saves even more walk alone length than what has been shown in Figure 12. Hence, the results hold true even with this assumption, although there remains the scope of improving the existing walk-sharing model by incorporating the provision of more realistic pedestrian route choice.

7.2.7 *'Trustworthy' walking companion*

Reluctance to share a ride with strangers has been major barrier to high participation rates in ridesharing programs (Amey, 2010; Chaube, Kavanaugh, and Perez-Quinones, 2010; Wessels, 2009). People are more likely to trust a person they know as opposed to a person they do not. This reasoning is even more profound when it comes to spending a significant amount of time with a person in spatial proximity, as is common in ridesharing. Chaube, Kavanaugh, and Perez-Quinones (2010) reported that 98% of the community of Virginia Tech University were willing to accept a ride from a first-degree friend, 69% from a second-degree friend, and only 7% from a stranger. Furthermore, the survey also reported that detour tolerances were significantly lesser while ridesharing with strangers.

The challenge is more acute in walk-sharing, as walk-sharing fundamentally aims to improve the urban walking experience in terms of safety and safety perception. If they feel unsafe due to their companion, then walk-sharing poses a safety challenge rather then solving it. Hence, it is of utmost importance that pedestrians are matched with a 'trustworthy' companion. While social preferences of the community were investigated via the survey presented in Chapter 5 and same gender preference was incorporated in the matching algorithm of the walk-sharing model in Chapter 6, further improvements can be made to understand the effects of trust on walk-sharing and for more appropriate matchmaking.

In a non-commercial setup, social network connections can be exploited for matchmaking in walk-sharing. From the modelling perspective, pedestrian agents could be programmed to have preferences to accept walk-sharing requests from and up to primary, secondary and tertiary social network connections. Wang, Winter, and Ronald (2017) had tested the impact of social media friendships and their spatial distributions on the performance of ridesharing systems. Similar research can be conducted in the walk-sharing domain. In a commercial setup, people willing to participate in walk-sharing can be subjected to a security screening. For example, online police checks can be mandated in the registration process of walk-sharing, to ensure that even strangers can trust their assigned companions to a degree. Post registration, a rating and review system could help users provide personal feedback on their experience with past walk-sharing companions. This is already prevalent in popular commercial shared mobility platforms such as Uber, and can be implemented in a future walk-sharing platform, providing users with reliable objective measures to trust their companions.

7.2.8 *Multiple walking companions*

This thesis introduced a rudimentary form walk-sharing where matchmaking is performed in a pairwise manner. This means, only two people are matched to each other to participate in walk-sharing at a time. The scope of this thesis only includes this 'single walking companion for a single journey' scheme. Future research needs to explore the scope for walk-sharing in both pairwise and non-pairwise multiple companion matching.

This includes matchmaking happening in a pairwise manner for a single journey, but with multiple companions. For example, people could share portions of their walking trip with multiple companions, but with one companion at a time. Matchmaking may also incorporate the scope of walk-sharing in groups of more than two people. For example, three of more people having similar spatio-temporal interests share a walk. All of them could share the same meeting point and separation point, or there could be multiple meeting and separation points suitable for the participants. There is also the scope for dynamic walk-sharing, where willing participants can join existing walk-sharing groups (ones who had already started their journey), and therefore the group size changes with time, and people hop on and off from the walk-share as per their convenience.

7.2.9 *Validation of results*

This thesis introduces walk-sharing as an intervention to improve walking experience of pedestrians in outdoor urban spaces. Walk-sharing is at a rudimentary stage of research, with real-world implementation substantially distant beyond further rigorous research and surveys. Hence, validation of the calibrated model is unfeasible at this stage of research. However, the model was developed via application of widely accepted pedestrian behavioural characteristics, and was calibrated using results of the survey. Additionally, proof of concept was established in Chapter 4. Therefore, the results obtained from the calibrated walk-sharing model are reliable.

7.2.10 *Relationships between critical factors*

This thesis assumes the independence between the critical factors (parameters involved in the model). There may exist empirical correlations between these parameters. For example, people might be willing to wait longer if their trip is longer. These relationships are beyond the scope of this thesis, but definitely opens up a new avenue for future work, where relationships between these independent variables are explored in detail via additional surveys involving choice-based experiments.

7.2.11 *Economic feasibility*

While the scope of this thesis included the theoretical and practical viability of walk-sharing using spatio-temporal and social parameters, the economic feasibility of walk-sharing was not tested. Participation in walk-sharing could mean less use of private and public transport. This would mean financial benefits in terms of fuel savings and ticket prices. It could also mean modal shift from private to public modes of transport. For example, people could avail public transport involving a longer walking leg because they now feel safer to walk, instead of commuting via private vehicle. This would mean no significant financial benefits (assuming fuel cost and ticket prices to be similar), yet substantial fuel savings, especially for longer journeys. Also, walking to a destination and using public transport usually involves more time, and hence could be financially costly from that perspective. From a community perspective, walk-sharing would mean significantly lesser harmful fuel emissions, and also improved health benefits to people, thereby potentially reducing public health costs. Quantifying all these costs and benefits is challenging. Hence, testing for the economic feasibility of walk-sharing is complex, and will require comprehensive research and modelling. Hence, the scope of this thesis was unable to accommodate the testing for economic feasibility of walk-sharing.

7.3 CONTRIBUTIONS OF THIS THESIS

This thesis has proposed walk-sharing, a smarter way to improve the uptake of walking in mode share by improving the safety perception of people about walking for transport. By ensuring safety perception of pedestrians, walk-sharing makes walking more attractive to people, thereby reducing the share of motorised vehicles, especially for short-distance trips and leading to more sustainable urban living. Additionally, this thesis investigates the viability of walk-sharing in a real-world university scenario by exploring its performance, and objectively measures the capacity of walk-sharing in terms of safety and safety perception improvement in relation to walking. The major scientific contributions of this thesis are summarised below:

1. The primary contribution of this thesis was the introduction of the novel concept of walk-sharing itself, which is a smarter intervention aimed to reduce fear of crime among pedestrians, thereby improving their safety perception and consequently, their propensity for walking. Walk-sharing bypasses the limitations of the existing approaches by being proactive, less data-driven, scalable and transferable. This contribution encompassed the introduction of walk-sharing, proposal of a conceptual model, outlining its benefits, costs and critical factors that drives its performance.
2. The second contribution of this thesis was the technical (theoretical) viability of walk-sharing in a real-world scenario. This contribution included the materialisation of the conceptual model into an agent-based simulation model for objective performance measurements, the investigation of the sensitivity of the performance of walk-sharing against the varying levels of critical factors, and finally the simulation of the walk-sharing model in a real-world scenario to understand safety improvement capacity, while checking for acceptable cost levels.
3. The third contribution of this thesis was the knowledge obtained on the community acceptance of walk-sharing. This contribution involved gathering information on the public perceptions on walk-sharing via a web-based survey viz., understanding their likelihood of participation in walk-sharing, their spatio-temporal and social preferences. It also involved detailed analysis of survey responses to gain deeper insights on the distribu-

tions of the preferences related to the costs of walk-sharing, and investigating whether these preferences were governed by the socio-demographic characteristics of the respondents.

4. The fourth and final contribution of this thesis was the practical viability of walk-sharing in a real-world data-driven urban scenario via calibration of the base walk-sharing model with parameter thresholds and distributions derived from the survey. This way the practical viability of walk-sharing could be objectively measured using relevant performance metrics viz., waiting time, detour length, walk alone length, matching rate, and safety index.

7.4 FUTURE DIRECTIONS

The final section of this thesis outlines the identified future directions upon which research on walk-sharing can proceed further.

7.4.1 *Multiple walking companions*

The scope of matchmaking in this thesis is limited to pairwise matching, or in other words 'single walking companion for a single journey'. Future research will add additional layers of complexity needed in the agent-based model to expand matchmaking beyond the presented form, as was discussed in Section 7.2.8. For example, in the cases where people could be matched with more than one companion, they will have multiple meeting and separation points instead of one. As matches can even be made when a pair of people have started their journeys, the current estimation of pre-defining a meeting and a separation point will have to be expanded to a more dynamic calculation. This would lead to the definition of additional parameters, such as proximity of origin to suggested routes of ongoing walk-sharing groups. Clearly, a detailed rigorous research is needed to improve the scope of the walk-sharing model in this regard, which is therefore left for future work.

7.4.2 *Exploring more efficient matching heuristics*

The heuristic matching algorithm implemented in the walk-sharing model is not optimised. Ridesharing literature exhibits several state-of-the-art optimised matching algorithms that can be implemented in the presented walk-sharing model. The incorporation of a more sophisticated algorithm for improving the efficiency of the match-making process can only upgrade the performance and efficiency of walk-sharing. Therefore, future work needs to involve improvements to the walk-sharing algorithm by making it more sophisticated. Other heuristics could also be implemented while calculating meeting and separation points, such as suggesting well-known or visible landmarks as possible meeting points.

7.4.3 *Weighting of distance and time components*

This thesis has considered uniform weights for all distance and time components while calculating parameter values. For example, greater walk-alone distance nearer to the home of a person (where the person may feel safer than other places at critical times) might be preferred over walk-alone distance near a desolated transit stop. Similarly, this could be applicable to waiting time. This means, weights of these distances and times would vary based on the perception of the user. However, this is beyond the scope of this thesis, as addressing this heterogeneity (as a result of comfort and familiarity with certain areas) needs careful consideration and rigorous research. Future work needs to address this aspect by acquiring relevant supporting information via additional surveys.

7.4.4 *Testing the viability of walk-sharing in other scenarios*

While this thesis had presented the performance of walk-sharing in a university campus scenario, the developed model could easily be transferred and used in other scenarios. Future work needs to involve using the base walk-sharing model to test the performance of walk-sharing in different, and possibly more challenging scenarios, to understand what kind of urban spaces will walk-sharing be more effective in. However, this would need pedestrian mobility data for such scenarios, and necessary calibration of spatio-temporal and social parameters within the model.

7.4.5 *Exploring social network connections for matching with companions*

Social networks have been widely exploited for matchmaking purposes in shared mobility platforms. Researchers have investigated the effects of spatio-temporal distribution of social network connections on the performance of such shared mobility modes. With safety perception being paramount in case of walk-sharing, social network connections and related matching preferences of people could be used to improve the matchmaking algorithm. As people would prefer to share a walk with a closer social network connection, future work involving matchmaking using such methods would improve the walk-sharing experience, and possible improve the participation rates of walk-sharing.

7.4.6 *Further theoretical simulations*

To understand the sensitivity of walk-sharing with other critical variables, further theoretical simulations should be conducted. Future work would involve investigating the performance of walk-sharing under different origin-destination (OD) structures. For example, theoretical simulations in Chapter 4 explored only many-to-many OD structure. Future work needs to involve testing the performance of walk-sharing under one-to-many (walking to different homes from the same shopping centre), many-to-one (walking to the same shopping centre from different homes) and one-to-one (university campus to one major public transport hub in suburbs) OD structures. Also, the performance of walk-sharing would be tested under different types of synthetic network structures (uniform grid, radial).

7.4.7 *Investigating the environmental impact*

While walk-sharing is primarily directed at the improvement in safety and safety perception of pedestrians and around walking in general, it has potential indirect benefits as well. As walk-sharing makes walking a safer proposition for the community, walking for transport becomes more attractive as a mode to people who would have availed alternatives otherwise. Therefore, walk-sharing encourages a modal shift, from motorised, non-sustainable and private modes of transport such as cars and motorbikes, to a sustainable and active mobility mode, walking. As a result, walk-sharing has two indirect positive effects on the environment.

Firstly, by increasing the proportion of pedestrians, walk-sharing helps encourages people to walk for transport and increase the amount of walking in their daily routines. Outdoor walking has been proven to improve not just physical, but mental health of people. Therefore, walk-sharing has long-term public health benefits. Secondly, as people walk more, they avail motorised forms of transport less often, especially for short-distance trips. This results in reduction in carbon emissions and reduces traffic congestion, which not only has positive environmental impacts, but also public health benefits. Future research will include studies conducted at estimating such indirect effects of walk-sharing on the community.

7.5 VISION

7.5.1 *Integration with Mobility as a Service*

Mobility as a Service (MaaS) is a vision in future mobility where people travel via a combination of private, public and shared transportation modes, all integrated in to a single platform via which the user can choose, book and pay for their trip. According to the white paper published by Cole (2018), "*Mobility as a Service is a combination of public and private transportation services within a given regional environment that provides holistic, optimal and people centered travel options, to enable end-to-end journeys paid for by the user as a single charge, and which aims to achieve key public equity objectives*". As MaaS aims to keep a healthy balance of shared vehicles on roads, while encouraging active mobility modes to reduce the overall impact of transportation on the environment, walking for transport becomes a significant mode of mobility in such an integrated multi-modal end-to-end mobility system (Cole, 2018), given that every transit trip begins and ends with walking (Ratner and Goetz, 2013; Tilahun et al., 2016).

As a safe first/last mile (FLM) journey encourages people to use public transport services more often, and as walking is the most common mode for FLM in urban areas, several studies have looked at inferring the pedestrian-friendliness of FLM journeys, or derive routes offering the best possible walking experience (Naharudin, Ahamad, and Sadullah, 2017). However, proximity to public transport stops is not the only governing factor for the attractiveness of an FLM journey. Fear of crime acts as a major inhibition to pursuing FLM journeys (Kim, Ulfarsson, and Hennessy, 2007; Tilahun and Li, 2015). Therefore, there is a considerable prospect for walk-sharing in MaaS.

Chapter 2 had discussed the advantages of walk-sharing in improvement of safety perception and reduction in fear of crime among pedestrians. While existing studies aim to recommend pedestrian-friendly routes for FLM (Naharudin, Ahamad, and Sadullah, 2017), such routes may always not be viable (longer detours) thereby reducing the attractiveness of an FLM journey, and sometimes not even possible at certain times of the day. However, Chapter 6 had quantified the prospect of walk-sharing, with the calibrated walk-sharing model delivering promising results in an urban scenario. Walk-sharing could seamlessly be integrated into an existing MaaS system to resolve the safety inhibitions of pedestrians in FLM journeys. As multi-modal journeys are booked via an MaaS platform using spatio-temporal information of the users, the system will compute and recommend, depending on the requirement of the users and/or the time of the day, shared walking journeys to and from public transport stops, all in one single platform. At times, this could also result in availing an alternate nearby transit stop where demand is higher, and therefore more potential participants for walk-sharing. Hence, walk-sharing could be the much needed smarter intervention that bypasses the drawbacks of existing studies, ensures walking companionship, reduces fear of crime among pedestrians, enhances the FLM walking experience, and most significantly, reduces motorised trips and improves the uptake of public transport services.

7.5.2 *Incentivised walk-sharing setups*

While this thesis has proposed walk-sharing as a purely social endeavour devoid of commercial angles, there is enough promise for incentivisation and commercialisation of walk-sharing. Commercial shared mobility platforms such as Uber, Lyft, who are already prominent in the ride-hailing and vehicle sharing business, could be appropriate stakeholders when it comes to developing a commercialised walk-sharing service. This would mean people in need of walk-sharing could book a walk-share on the go via their smartphones for a certain sum of money, similar to ride-hailing services. Walk-sharing escorts, similar to Uber drivers, could pick them up from their origin and drop them at their destination, while being reimbursed for their efforts.

One possible use-case for walk-sharing could be companionship services for older adults while walking. Older adults (people aged 65 years or more) are the fastest growing age bracket of the western world population. 150 minutes a week of moderate intensity activity such as brisk walking is recommended for this age group (Australian Government - Department of Health, 2021; Centers for Disease Control and Prevention, 2021), to which, only 30-40% of people adhere to (Moran et al., 2014). The minimum recommended physical activity is essential to preserve their quality of life and manage health care costs (Vogel et al., 2009). One of the major reasons for this is the fear of crime when walking outdoors. A significant number of older adults report crime-related fears (Roman and Chalfin, 2008; Ron et al., 2004). Walk-sharing could intervene by pairing people from this age bracket with volunteering younger people, who would escort them to the supermarket, while being paid for their service. Here, walk-sharing makes walking not only a safer proposition for older adults, but also makes it more attractive by assigning a companion. Given loneliness and social isolation are significant challenges in older adult populations (Ring et al., 2013), a companion provides an avenue for a brief, yet significant, social interaction. Although walk-sharing (walking for transport) alone may not be able to satisfy the minimum recommended physical activity level for older adults, it still promises significant improvements in magnitudes of daily physical activity.

Another possible use-case for walk-sharing could be companionship services for Visually Impaired People (VIP). *Travel Hands* (`https://www.travelhands.co.uk/`), a product of VIP World Services (`https://www.vipworldservices.com/`), is an existing pick-up and drop service in the United Kingdom that "*pairs a VIP with sighted and verified volunteers to walk together towards their similar destinations*". Similar to ride-hailing services, "*a VIP can submit a trip request that is automatically sent to a volunteer near them, alerting the volunteer to their location.*

The accepting volunteer will then come and pick-up the VIP and walk towards the requested destination." However, this service is localised, and offer services only in London. Also, this is a call centre service, meaning people have to call a number to access this service, and there is a person acting as a mediator who assigns a suitable companion to the user. In an age of smartphones, and with *Accessibility* options in smartphones to assist VIPs, a commercialised walk-sharing service could provide an all-in-one platform to book such companions on the go with automated dynamic matchmaking at the backend, without the need for manual moderators.

Therefore, in a service-based setup, the 'costs' of walk-sharing, such as waiting time (by booking in advance), walk-alone distance (pick up and drop off), detour length (person availing the service does not compromise on shortest route) are reduced considerably, if not completely, as monetary costs increase (payment made for availing the service). Incentivisation can increase participation in walk-sharing, and consequently increase walking in people's everyday lives, thereby leading to safer, healthier and most sustainable cities.

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