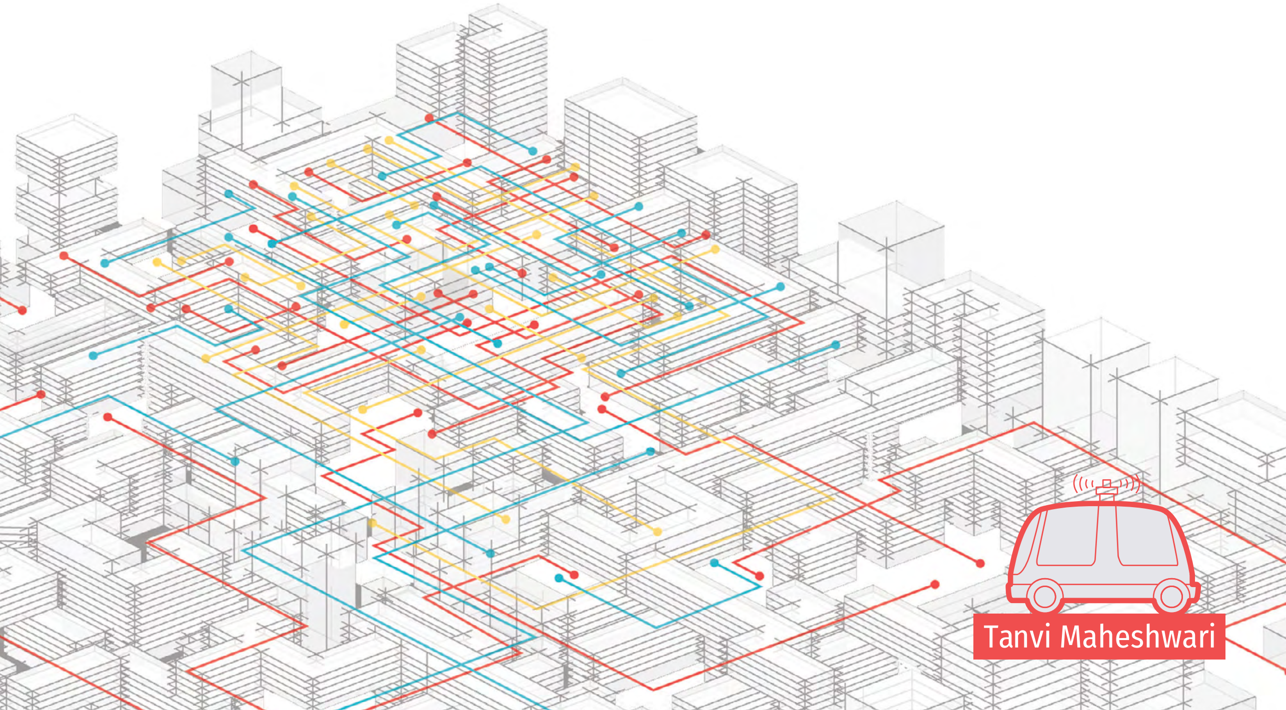
Diss. ETH No. 26976

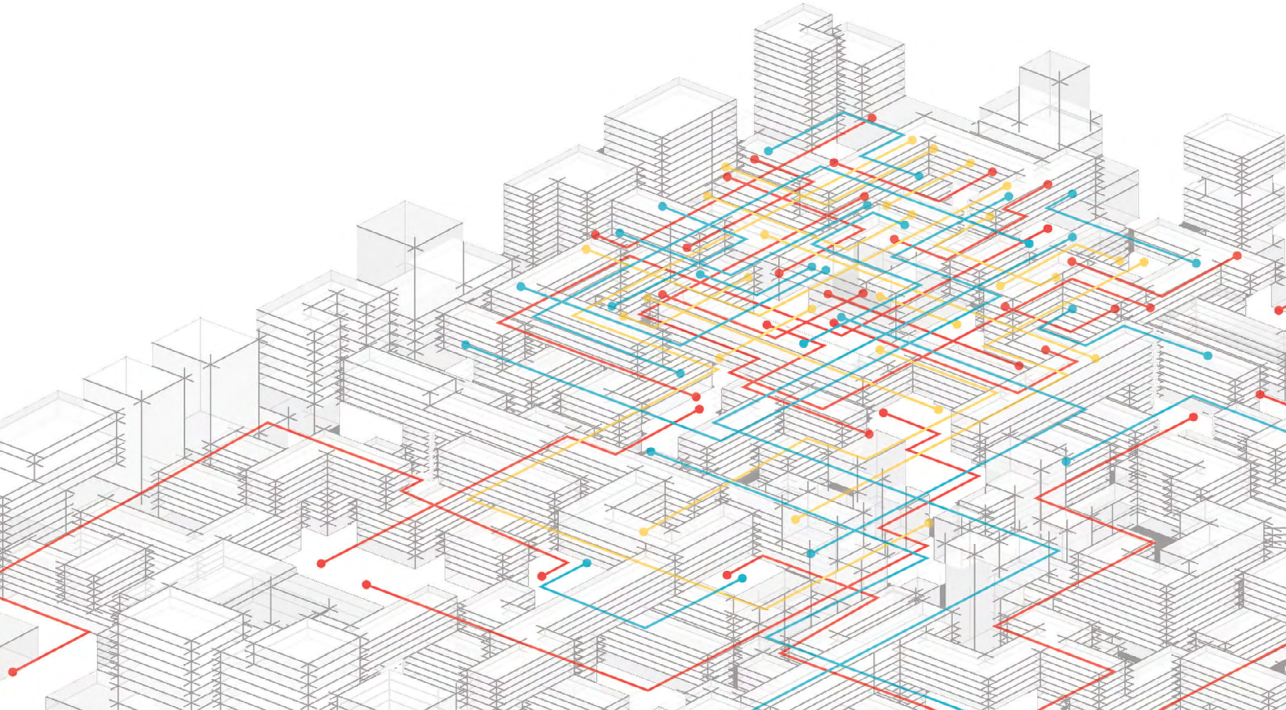
AN URBAN DESIGN RESPONSE TO THE TECHNOLOGICAL SHIFT IN TRANSPORTATION

How to conduct urban design with vehicle automation, sharing and connectivity



Tanvi Maheshwari

Recent developments in vehicle automation, connectivity, electro-mobility, and ridesharing platforms, collectively termed as the 'technological shift in transportation', are expected to transform urban mobility patterns. But there is enormous uncertainty regarding how this may impact cities. Urban form and transport flows influence each other through a complex reciprocal relationship, and urban design and planning can play a decisive role in steering these impacts. This research investigates the impacts of the technological shift in transportation on cities, develops novel methods to conduct urban design in this context, and proposes urban and design planning strategies in response, based on a series of 'Design Experiments'. These strategies are illustrated through an urban design response to the technological shift in transportation for a Singapore New Town. This response ranges from retrofitting interventions in the short term, structural changes in the medium term, to a radical transformation to a 'Post-Road City' in the long term.



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An Urban Design Response to the Technological Shift in Transportation

How to conduct urban design with vehicle automation, sharing and connectivity

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. Sc. ETH Zurich)

presented by

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Abstract

Recent developments in vehicle automation, connectivity, electro-mobility and ridesharing platforms are expected to transform urban mobility patterns and consequently reshape urban form. Historically we have seen that introduction of new transportation technologies has influenced new urban models and altered development patterns. An often-cited example in this regard is the rise of the private automobile which brought about a rise in suburban development. Urban form and transport flows have a complex two-way relationship where changes in one has repercussions on the other. Given this interdependency, the impacts of the recent technological developments, collectively termed as the 'technological shift in transportation', must be investigated within urban design and planning disciplines.

There is enormous uncertainty surrounding how the technological shift in transportation may impact cities, and urban design and planning can play a decisive role in steering these impacts. The efficiencies and safety benefits of vehicle automation have been widely stated in support of its widespread implementation. At the same time, critics warn against dire environmental and social consequences of reckless implementations that do not take into consideration the complex interdependencies of the technology with the broader social, economic and physical context. This research examines the impacts of the technological shift in transportation on cities and urban form and searches for appropriate methods to conduct urban design in this context.

The interplay of urban form and transport flows is investigated by integrating multi-agent simulations within the urban design workflow, through a series of 'Design Experiments'. Singapore's residential New Town model is chosen as a test site to conduct these design experiments, which aim to understand what design strategies can help us maximise the benefits of the technological shift and minimise its potential risks. Piecemeal design strategies are assessed through simulations to understand changes in transport flows over time and study emergent patterns. These insights inform a set of urban design and planning strategies in response to the technological shift in transportation a new structural model of the Singapore New Town for the short, mid and long term future. These proposals range from retrofitting the New Town in the short term to modifying the model structurally in the mid-term, moving towards a radically different 'Post-Road City' in the long term.

Zusammenfassung

Die jüngsten Entwicklungen in den Bereichen autonomes Fahren, Vernetzung, Elektromobilität und Plattformen zur gemeinschaftlichen Nutzung von Fahrzeigen werden voraussichtlich städtische Mobilitätsmuster verändern und damit Stadtform neu gestalten. In der Vergangenheit haben wir gesehen, dass die Einführung neuer Verkehrstechnologien die Entstehung neuer Stadtmodelle beeinflusst und urbane Entwicklungsmuster verändert hat. Ein oft zitiertes Beispiel in dieser Hinsicht ist der Aufschwung des privaten Automobils und das darauffolgende Wachstum der Vorstädte. Städtische Form und Verkehrsströme stehen in einer komplexen Wechselwirkung, in der Veränderungen in einem Bereich Auswirkungen auf den anderen haben. Angesichts dieser gegenseitigen Abhängigkeiten müssen die Auswirkungen der neuesten technologischen Entwicklungen, die unter dem Begriff “technologischer Wandel im Verkehrswesen” zusammengefasst werden, in den Disziplinen Städtebau und Stadtplanung untersucht werden.

Es ist noch ungewiss, wie sich der technologische Wandel im Verkehrswesen auf Städte auswirken könnte, wobei sicherlich Stadtgestaltung und -planung eine entscheidende Rolle bei der Steuerung dieser Prozesse spielen werden. Effizienz und Sicherheit wurden als Vorteile des autonomen Fahrens bei ihrer Einführung angepriesen. Gleichzeitig warnen Kritiker vor gravierenden ökologischen und sozialen Folgen rücksichtsloser verkehrspolitischer Implementierungen, die die komplexen Interdependenzen von Verkehrstechnologie und sozialem, wirtschaftlichem und physischem Kontext ausser Acht lassen. Die vorliegende Forschungsarbeit untersucht die Auswirkungen des technologischen Wandels im Verkehrswesen auf Städte und Stadtgestalt und sucht nach geeigneten Methoden, um Stadtgestaltung in diesem veränderten Kontext durchzuführen.

Das Zusammenspiel von urbaner Form und Verkehrsströmen wird durch die Integration von Multi-Agenten Simulationen als Bestandteil des städtebaulichen Entwurfsablaufs mittels einer Reihe von Entwurfexperimenten untersucht. Singapurs Wohnmodell der New Town wird als Testgelände für die Durchführung dieser Experimente ausgewählt, um zu verstehen, welche Entwurfsstrategien die Vorteile des technologischen Wandels maximieren und gleichzeitig potenzielle Risiken minimieren. Vereinzelte Entwurfsstrategien werden durch Simulationen bewertet, um Veränderungen von Transportströmen im Laufe der Zeit zu verstehen und daraus entstehende Muster zu untersuchen. Diese Erkenntnisse dienen als Grundlage für eine Reihe von Städtebau- und Planungsstrategien die im Dialog mit dem technologischen Wandel im Transportwesen stehen und stellen ein neues strukturelles Modell der New Town in Singapore für die kurz-, mittel- und langfristige Zukunft vor. Diese Vorschläge reichen von der kurzfristigen Nachrüstung der New Town, über eine strukturelle Veränderung des urbanen Modells auf mittlere Sicht, bis hin zu einer langfristigen radikalen “Post-Road City”.

Acknowledgements

I wish to express my gratitude to Prof Dr Stephen Cairns, my supervisor, and Prof Dr Kay W. Axhausen, my co-supervisor, without whose generous support and encouragement this thesis would not have been possible. Dr Pieter Fourie was an incredible support through this whole process, not just with MATSim, but with his daily supervision, conversations and appropriate doses of a morale boost. I also owe a debt of gratitude to Dr Alex Erath without whose groundwork and firm support, I would not have embarked on this journey at all.

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Abbreviations

ABM	Agent Based Modelling
AI	Artificial Intelligence
AMoD	Automated Mobility on Demand
AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CARTS	Committee on Autonomous Road Transport for Singapore
DARPA	Defense Advanced Research Projects Agency
DRT	Demand Responsive Transit
DVRP	Dynamic Vehicle Routing Problem
EAV	Electric Automated Vehicle
ERP	Electronic Road Pricing
EV	Electric Vehicle
FCL	Future Cities Laboratory
HDB	Housing and Development Board
ICT	Information and Communication Technology
IoT	Internet of Things
IoV	Internet of Vehicles
LTA	Land Transport Authority
MaaS	Mobility as a Service
MATSim	Multi Agent Transportation Simulation
MoT	Ministry of Transport
NUS	National University Singapore
PMD	Personal Mobility Device
SAV	Shared Automated Vehicle
SEAV	Shared Electric Automated Vehicle
SEC	Singapore ETH Centre
SI	Slot-based Intersections
SMART	Singapore-MIT Alliance for Research and Technology
TNC	Transportation Network Companies
TOD	Transit Oriented Development
URA	Urban Redevelopment Authority
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VKT	Vehicle Kilometres Travelled
VRU	Vulnerable Road Users

1 Technological Innovations in Transportation and the Role of Urban Design

Motivation for this thesis

The invention of the private automobile in the late nineteenth century had arguably been the most significant technological change in urban transportation since trains. Its widespread proliferation not only fundamentally changed how we move through the city, but the shape of the city as well. This dominance of the car in urban transportation has been rather stable through the last century, supported by sporadic technological improvements and upgrades. However, in recent years, new technological innovations in vehicle autonomy, mobility-as-a-service, electric and connected vehicles, are challenging this stable state. If these technological innovations signal a broader shift in urban transportation, urban design as a discipline cannot remain a passive observer, but must proactively respond to this shift and even steer it to produce desirable urban futures.

Technological innovations

This thesis aims to focus on the challenge that technological innovations in transport pose for the field of urban design and planning, and how such technologies can support innovative models for future cities. Many recent developments that contribute to this wider context sparked this investigation. From humble beginnings in 2009, today, Uber has become a global giant, and carsharing companies are ubiquitous across all major cities in the world. The electric vehicle market has also seen accelerated growth, with only 380,000 electric cars in circulation in 2013, to more than 3 million in just four years (International Energy Agency, 2018). At the same time, 5G technology is developing swiftly and could transform the automotive industry, with the share of 5G connected cars expected to climb up to 94% by 2028 (Baghdassarian, 2019).

Automated vehicles

Developments in vehicle automation have been central to all these technological innovations. In 2004, 15 self-driving cars competed in the DARPA (Defense Advanced Research Projects Agency) Grand Challenge, a race between self-driving cars. None of the participants could complete the entire course, and Carnegie Mellon's Sandstorm travelled the farthest (7.8 km) (see Figure 1.1). The competition triggered an accelerated pace of development in vehicle automation technology. As of January 2020, Waymo's self-driving car has completed 20 million miles of autonomous driving (Reuters, 2020), and Singapore has announced opening up of more than 1000 km of public roads for testing such vehicles (Toh, 2019a).

Technological shift in transportation

In this research, these technological disruptions are collectively referred to as the *'technological shift in transportation.'* While individually these innovations are sometimes viewed as mere upgrades on existing technologies, increasingly commentators are viewing them collectively as part of a broader shift. Klaus Schwab, the founder of World Economic Forum, described the 'staggering confluence of emerging technology breakthroughs… such as artificial intelligence (AI), robotics, the internet of things (IoT), autonomous vehicles…' as signalling a '*fourth industrial revolution*' (Schwab, 2017). Others have described the rise of these set of technologies as a '*Cambrian moment*' transforming the foundations of the automotive industry (Ferràs-Hernández et al., 2017), '*Transportation 2.0*' (Emadi, 2011), and as a 'revolution' (Sperling, 2018).

Need for an urban design response

It is uncertain if these technological developments truly represent a paradigm shift in transportation in the Kuhn-ian sense, and some critics even find such claims exaggerated given the current state of technology. However, if the pace of technological development and adoption is anywhere near what industry experts predict, they will undoubtedly have far-reaching impacts, potentially transforming urban form in the long term, as was the case with the private automobile.

Figure 1.1 Carnegie Mellon's off-road driving robot, Sandstorm

Red Team's car that went the furthest in the 2004 DARPA Grand Challenge Source: cs.cmu.edu

1.1 Cities and Transportation Technology

Urban form and technology are related

The technology of mobility sits in a context; in this case, the city fabric itself, which has historically been shaped by developments of key infrastructural technologies (Hodson and Marvin, 2009). The shift from an agrarian to industrial mode of production at the beginning of the 19th century led to urban expansion and, eventually, suburbanisation (shown in Table 1.1). Subsequently, the transition from an industrial mode of production to information-based society by the end of the 20th century resulted in what Manuel Castells refers to as the '*Informational City*' (Castells, 1992). Consideration of the city form, its streets, buildings, and networks, is a crucial aspect of the problem that this thesis aims to address, based on the strong relationship between urban form and transport flows.

Transportation technology and the shape of the city

Transportation technology played a vital role in the organisation of cities, from building scale, through changes in human activity patterns and space requirements, to the regional level, through changes in interactions between activities affecting densities and location choice (Brotchie, 1984). American geographer Adams (1970) identified four different 'transportation eras' linked to the development of specific transportation technologies in the context of mid-western American cities. The urban form steadily evolved from the walking-horsecar city to the city of electric streetcars and railway suburbs, to the automobile and freeway city of today, as illustrated in Figure 1.2. The spreading out of activities and low-density development as a result of high mobility enabled by the automobile is conspicuous in this diagram.

Development of private automobile

The arc of development of the private automobile and corresponding urban models, from the recreational automobile era to the freeway era, offers valuable lessons on the need for an urban design response to the ongoing technological shift in transportation. Similar to the DARPA challenge, the Chicago Times-Herald announced 'horseless carriage competition' in 1896, which was won by Duryea's gas-powered vehicle (Figure 1.3). The success of the race sped up the rate of automobile development in America, and the commercial production of private automobiles began a year later (Flink, 1990), establishing the petrol-powered private car as the transport mode of the future. Following this, between 1920-50s, the automobile became the centrepiece of futuristic urban visions.

Figure 1.2: Four-stage model of transport eras

Peter O. Muller's four-stage model of intra-metropolitan transport eras and associated growth patterns in America.
Source: Adapted from (Muller, 2004), 62

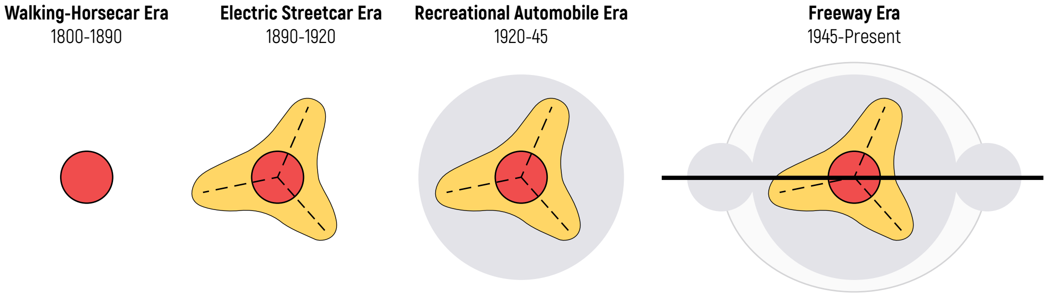

Table 1.1: Technology and Urban Development

Period	**Technology**	**Urban Form and Development**
Early industrial (1820-1869)	Railroad	Initial urban growth (e.g., population influx in cities)
Late industrial (1870-1919)	Electricity, Elevator, Telephone, Automobile	Expansion of cities, Beginning of urban dispersal (suburbanization)
Mass production metropolis (1920-1969)	Road building (e.g., highways)	Massive residential suburbanization, Beginning of commercial suburbanization
Post-metropolis (1970-present)	Personal computer, ICT (e.g., Internet)	Decentralization of metropolitan regions (e.g., polycentricity of suburban employment centres), Urban revitalization with technological advances, Global city network

Tracing the influence of technology on urban development from the early industrial period to the present
Source: (Maeng and Nedović-Budić, 2008), Table 2

Urban visions inspired by the promise of the car

The benefits of fast, convenient and cheap private mobility lured planners and policymakers into designing cities that eulogised the private car, initially failing to consider its potential pitfalls. Proposals such as Corbusier's *La Ville Radieuse* designed in 1930 (Figure 1.4) advocated physical separation between pedestrian and vehicular movement through multiple levels, indicating a recognition of the growing importance of the automobile in urban design. These ideas reached a crescendo in GM's Futurama exhibit at the 1939 World's Fair (Figure 1.5) where Norman Bel Geddes designed 'trench-like lanes' that would keep cars apart from all other traffic on automated highways (Geddes, 1940).

Waning enthusiasm for the private car

The inherent belief that cities could be beneficially 'transformed' by providing for better automobile travel led to large scale car-oriented development with spreading out of activities and low-density development. As the detrimental impacts of car-oriented planning became evident, the initial enthusiasm for the private car began to wane. By the early 1960s, radical urbanists like Jane Jacobs, Lewis Mumford and Christopher Alexander began questioning the highway-based city, recognising that the mere deployment of new technology could not improve the present situation (Cannon, 1973). Urban models began to take a more humanist approach, placing people rather than technology at their centre, such as the Charter of New Urbanism (2000).

Lock-in effects of the automobile

Even as the excessive optimism for the private automobile withered away, the effects of the automobile revolution continued to ripple through the urban landscapes. We are now inextricably locked into the *'system of automobility',* a term coined by sociologist John Urry, pioneer of the *'mobilities turn*' in social sciences in the 1990s. The system of automobility is attributed to a path-dependent pattern of development of society and urban form, stemming from the automobile. Since the pace of change of urban form and infrastructure is slow, it is difficult to break out of the lock-in effects of automobility. In order to do so, we need to examine the possibilities of 'turning points' (Urry, 2004).

Automated vehicle revolution

Does the rise of vehicle automation technology and other enabling innovations signal such a turning point, towards a fifth era in Adams' four transportation eras? At present, the arc of technological development seems promising, with AVs already deployed on roads in Europe (Alessandrini et al., 2014), Singapore (Toh, 2019b) and 24 other pilot cities in the United States (Coren, 2018). China has also set a target of full autonomy for 10% of all vehicles by 2030 (The Aspen Institute, 2017). Although fully automated vehicles are expected to transform transport systems (Heinrichs, 2016), more cautious authors believe that it will require several decades before the advantages of automated vehicles can be realised (Cools et al., 2016).

Building cities around technology

Many factors, beyond the state of the technology itself, such as socio-economic conditions, design and policy, determine the entrenchment of technology in the society, and it is too early to predict if the automated vehicle technology will unfold on a similar scale as the private automobile. This thesis takes the position that the technological shift in transportation has the potential to dismantle the current system of automobility and establish new, more people-friendly and sustainable patterns of mobility. In order to do so, we employ a multi-disciplinary methodological framework to develop an appropriate urban design response to the technological shift in transportation.

1.2 Research Questions

The technological shift

The research objectives will be tackled through three related lines of questioning. The first aims to understand how the technological shift will impact cities as a whole. What technologies are a part of this shift? Is there a technological shift underway in transportation, or is it merely a technological upgrade? Moreover, if there is such a shift underway, what impact does it have on the city?

The role of urban design

Subsequently, we need to delve deeper into the question of if and how urban design can play a role in influencing the impacts of the technological shift. How can we conduct urban design if the new conditions imposed by the technological shift renders conventional urban design methods and procedures obsolete?

The urban design response

Finally, the ultimate research question deals with what should be the appropriate urban design response to the technological shift in transportation? What design strategies can be employed to help us maximise the benefits of these technologies and minimise their dangers? This response is developed through an empirical study based in New Towns in Singapore.

Figure 1.3 Duryea during the Chicago Times-Herald race
J. Frank Duryea, left, and race umpire Arthur W. White, right, in the 1895 Chicago Times-Herald race, the first automobile race in the U.S.
Source: Detroit Public Library (digitalcollections.detroitpubliclibrary.org)

Figure 1.4 Le Corbusier's La Ville Radieuse
La Ville Radieuse formed the basis of several urban plans during the 1930s and 1940s, including that of Brasilia. Source: (Le Corbusier, 1933)

Figure 1.5 General Motors' Futurama exhibit designed by Norman Bel Geddes in 1939

Source: Originally from General Motors, obtained from Computerhistory.org

1.3 Research Context

The L2NIC-AV grant

This research is part of a larger project funded by the Ministry of National Development to understand the impacts of automated vehicles on urban planning and transport supply in Singapore. The grant under the aegis of 'Land and Liveability National Innovation Challenge' (L2NIC-AV) programme[2], presented a unique opportunity to not only operationalise new design methods and apply the findings on a real-world test case but also to do so in a high-density Asian city, with potentially far-reaching consequences across the region. The positioning of this thesis within the L2NIC-AV study opened up access to multi-disciplinary experts from three academic institutes and policymakers from four Singaporean planning agencies. For more details on the project and related interactions, see Appendix 1.

Action research

The dual focus on real-world problems and developing solutions through collaboration made the L2NIC-AV project ideally suited for 'action research'. Action research is defined as a participatory and democratic process of research to develop practical knowledge (Reason and Bradbury, 2001), marked by a (1) problem focus, (2) action orientation, (3) cyclical process and (4) collaboration/participation (Peters and Robinson, 1984). This research draws heavily on the inputs from and discussions with stakeholders involved in the L2NIC-AV project, through a series of workshops and meetings conducted over the duration of the project (see Appendix 1). This approach deviates from a strict positivist view of science, which aims to contribute to general knowledge while remaining objective and value-free (Brydon-Miller et al., 2003; Elden and Chisholm, 1993), but instead embraces 'socially constructed knowledge' embedded within a value system.

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[2] The L2NIC-AV project grant was awarded to a consortium of three academic institutes – MIT SMART (Singapore-MIT Alliance for Research and Technology), Future Cities Laboratory, SEC (Singapore ETH Centre) and NUS (National University Singapore) in 2017. There were four Singapore agencies officially collaborating on this project – Ministry of Transport (MoT), Urban Redevelopment Authority (URA), Land Transport Authority (LTA) and Housing Development Board (HDB). L2NIC stands for 'Land and Liveability National Innovation Challenge', a long-term, multi-agency effort that recognises land as important resource for Singapore, and seeks solutions to tackle land scarcity while maintaining liveability standards. The project brought together strong expertise in automated vehicles from urban planning, spatial analysis and transportation simulation, to study suitable urban design and AV operation schemes for Singapore's high-density tropical urban environment.

1.4 Thesis Structure

This thesis is broadly structured into two parts. The first, **Theoretical Investigation**, relies on literature review and horizon scanning as primary methods to

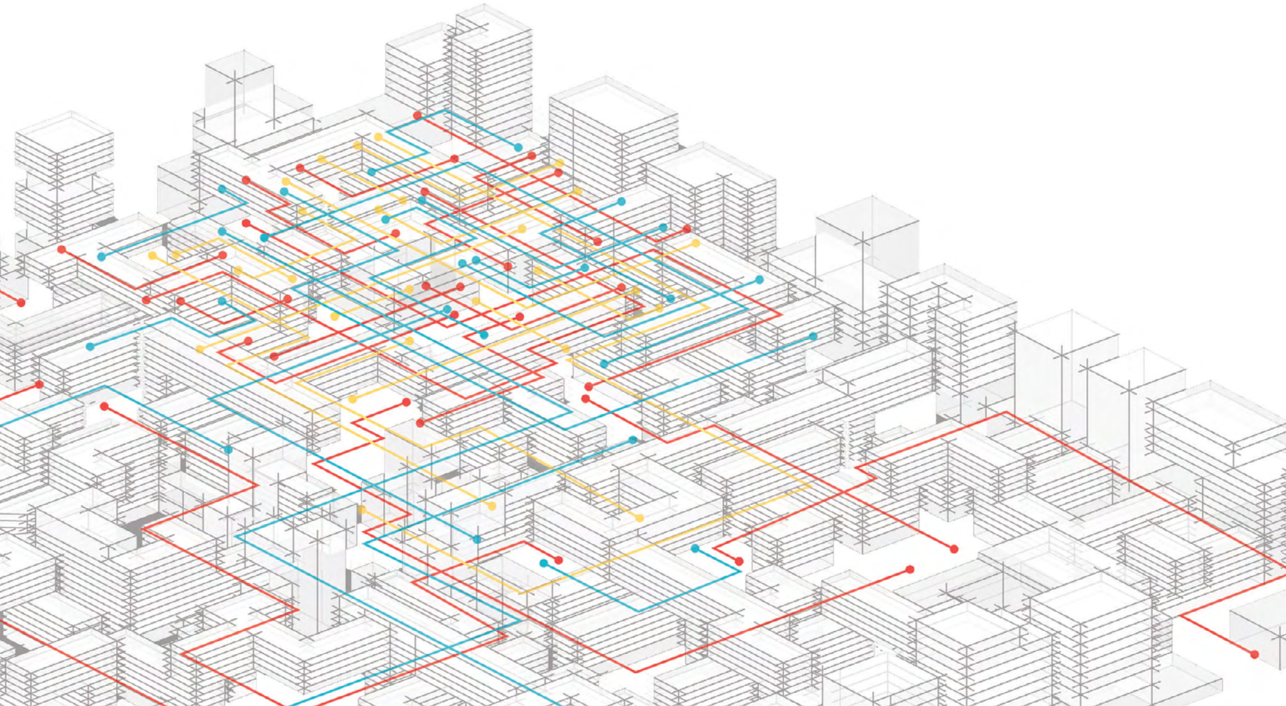
- Unpack the technological shift and understand the current state of the technology in **Chapter 2**,
- Understand the impact of the technological shift on cities in **Chapter 3**
- Develop a catalogue of urban design strategies commonly seen in contemporary urban design practice as a response to the shift in **Chapter 4**,
- Study the fundamental theoretical relationship between urban form and transport flows in **Chapter 5**
- Review the methodological relationship between urban design and transport analysis in **Chapter 6**, and
- Propose a new methodological framework to conduct urban design in the context of the technological shift in **Chapter 7**

The proposed methodological framework is operationalised on a test site, Singapore New Town, in the second part of this thesis. The **Empirical Study** follows three steps.

- First, we define the scope of the project and the limits of the parameter space, to build an 'exploratory model' of the test site – a typical Singapore residential New Town. **Chapter 8** describes how the model for design and simulation is constructed.
- Second, four 'Design Experiments', representing four questions of interest, are constructed and evaluated through an iterative design and simulation cycle using MATSim (Multi-Agent Transportation SIMulation). The results from the analysis and urban design recommendations that emerge from it are presented in **Chapter 9**.
- Finally, the results from the experiments inform the proposal for a new urban model for the Singapore New Town in response to the technological shift. This response manifests in three stages – retrofitting interventions in the short term, structural modifications in the mid-term, and a radically different urban model, the 'Post-Road City' in the long term. These stages are discussed in **Chapter 10**
- Some final concluding remarks and reflections on the practice, methods and limitations are discussed in **Chapter 11**.

PART 1

THEORETICAL INVESTIGATION



2 The Technological Shift

This chapter aims to develop an understanding of the technological shift in transportation by developing a working definition of 'technological shift in transportation' in the context of this research, and expanding on the five technologies that propel the shift: vehicle automation, sharing, electrification, sensing and connectivity and tailored vehicles.

2.1 Definition of Technological Shift

Technological innovations in transportation

The urban transportation sector has witnessed several technological innovations in the last two decades. The accelerated pace of development in vehicle automation technologies (The Aspen Institute, 2017), widespread implementation of platform based ride-hailing system in most major metropolitan regions around the world (Clewlow and Mishra, 2017), developments in affordable electric vehicles with constant improvements in batteries (Attias, 2016), and growing connectivity and sensing in our environment, marked by latest developments in 5G technology (Ge et al., 2017), are all examples of such innovations. These technologies – automation, vehicle sharing, electrification, connected vehicles - have been variously described as a series of isolated technological disruptions (Greenblatt and Shaheen, 2015; Wadud et al., 2016), that amount to a revolution when seen as a whole (Attias, 2016; Fagnant and Kockelman, 2015; Sperling, 2018).

Automobile and system of automobility

It is as yet unclear if these new technologies signal a change within the current paradigm or a shift in transportation paradigm, as was the case with the private automobile. A ‘paradigm’ here refers to considerations that range beyond the immediate characteristics of technological innovation itself to the broader social and economic context in which a given technological trajectory is embedded (Cantwell, 2019). The private car that locked us into what Urry (2004) refers to as, the ‘system of automobility’, includes not just the manufactured object of technology (the car), but a powerful complex constituted through technical and social and cultural interlinkages.

Fourth industrial revolution

There have been three paradigmatic systems since the first industrial revolution: the mechanical age, the science-based mass production age, and the information age (Cantwell, 2019). In 2017, Klaus Schwab, founder of World Economic Forum, described the ‘staggering confluence of emerging technology breakthroughs... such as artificial intelligence (AI), robotics, the internet of things (IoT), autonomous vehicles...’ as signalling a *‘fourth industrial revolution’* (Schwab, 2017). This points towards a broader society-wide techno-socio-economic paradigm shift that these technological innovations enable in part. However, whether they amount to a paradigm shift in transportation is uncertain, and some critics find such claims exaggerated given the current state of technology.

Definition of technological shift

This thesis argues that these emerging systems and technologies have the potential to coalesce and fundamentally shift existing mobility patterns. Urry (2004) makes a similar argument when he says that *‘AVs have the potential to integrate with other technologies and shock the system of automobility into a different pattern involving almost a complete break with the current car system’*. This convergence of transportation technologies is defined here as the *‘technological shift in transportation’*. In the following text, we discuss the rising dominance of five main technological innovations, and their potential to converge and reinforce each other.

2.2 Five innovations driving the Technological Shift

Technologies of potential integrations

The automated vehicle has been the centrepiece of the technological shift among other maturing or nascent technologies of potential integration. Several scholars have proposed a list of these enabling technologies. For example, Dia and Javanshour (2017) identify four enabling technologies, in addition to automated vehicles, that may revolutionise urban mobility - mobile computing, big data, Internet of Things (IoT) and cloud computing. To this list, Urry (2004) adds new fuel systems such as electric vehicles, new materials for constructing car bodies, smart card technology, a thrust towards 'new-realist' policy in transportation from the standard predict-and-provide models, and growing communications and internet connectivity. Of these technologies, many scholars (Burns et al., 2012; Greenblatt and Shaheen, 2015; Sperling, 2018) identify vehicle sharing as the most critical technological and business enabler that may dramatically disrupt the status quo. In this chapter, we will focus on five main technological innovations: vehicle automation, sharing, electrification, sensing and connectivity and tailored vehicles.

2.2.1 Automation

What is AV

Vehicle automation here refers to road vehicles that do not require a human driver to perform driving tasks such as navigation, lane-keeping and stabilisation. The classification of automated vehicles given by SAE (Society of Automotive Engineers) in 2016, is the industry standard accepted by all major stakeholders in the automotive field, summarised in Table 2.1. There are cars on the road today that already incorporate up to level 3 automation. However, there is ample evidence to suggest that the real benefits automation cannot materialise until we have full deployment of level 4 or 5 automation (or full automation), which does not require a driver at all (Kyriakidis et al., 2017). It is the fully automated vehicle that has captured the imagination of technologists, urbanists and futurists for over a century.

History of the idea of AV

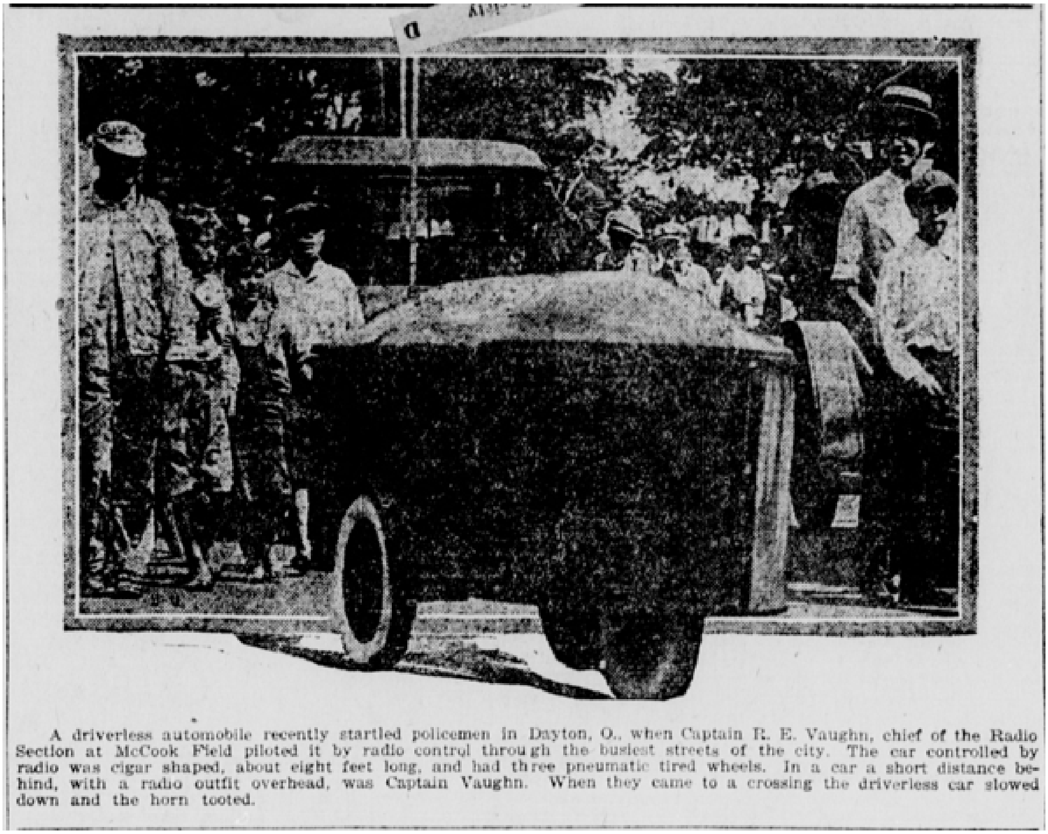
The first driverless car concepts emerged between 1920-40, both in fiction and reality. They ranged from the 'phantom autos' of the 1920s and 30s that were remote-controlled by the tapping of a telegraph key (see Figure 2.1), to the model of the Future American City with automated highways and driverless cars created by General Motors for the 1939 World's Fair Futurama exhibit (shown in Figure 1.5). After a brief hiatus during the second world war, the automobile and the automated highway returned to the centre of attention in the fifties and sixties, when the Federal Highway Act of 1956 led to large scale highway building across the US. Visuals like the ad for a driverless car in 1957 (see Figure 2.2), and 'Magic Highway' on a popular Disney TV show in 1958 (see Figure 2.5), stand testament to the fascination with the driverless vehicle at the time.

Table 2.1: SAE classification of levels of vehicle automation.

Level of Automation	Features
Level 0	Automated system has no vehicle control but may issue warnings.
Level 1	Driver must be ready to take control at any time. Automated system may include features such as Adaptive Cruise Control (ACC), Parking Assistance with automated steering, and Lane Keeping Assistance (LKA) Type II in any combination.
Level 2	The driver is obliged to detect objects and events and respond if the automated system fails to respond properly. The automated system executes accelerating, braking, and steering. The automated system can deactivate immediately upon takeover by the driver.
Level 3	Within known, limited environments (such as freeways), the driver can safely turn their attention away from driving tasks, but must still be prepared to take control when needed.
Level 4	The automated system can control the vehicle in all but a few environments, such as severe weather. The driver must enable the automated system only when it is safe to do so. When enabled, driver attention is not required.
Level 5	Other than setting the destination and starting the system, no human intervention is required. The automatic system can drive to any legal location and make its own decisions.

Source:Adapted from SAE Standard 'J3016' (2014)

Figure 2.1: An early driverless car or 'phantom auto'.
Published in The Daily Ardmoreite. August 12, 1921 Source: chroniclingamerica.loc.gov



A driverless automobile recently startled policemen in Dayton, O., when Captain R. E. Vaughn, chief of the Radio Section at McCook Field piloted it by radio control through the busiest streets of the city. The car controlled by radio was cigar shaped, about eight feet long, and had three pneumatic tired wheels. In a car a short distance behind, with a radio outfit overhead, was Captain Vaughn. When they came to a crossing the driverless car slowed down and the horn tooted.

Figure 2.2: A driverless car from an advertisement in 1957
Source: Americas Electric Light and Power Companies

R. One day your car may speed along an
d and steering automatically controlled by

electronic devices embedded in the road. Highways will be ma
by electricity! No traffic jams . . . no collisions . . . no drive

The Da Vinci Problem

It is interesting to note how a fully automated vehicle has remained 'just 20 years away' for almost a hundred years (Kröger, 2016), yet even by the end of the twentieth century, the driverless cars were nowhere near becoming a reality. Vehicle automation technology may have languished for decades because of the '*Da Vinci Problem*' (Lipson and Kurman, 2016), which arises when an inventor's vision cannot be implemented, not because of problems with the concept, but because other technologies that support the invention have not yet come into existence. Recent technological developments in transportation may help us to finally overcome the *Da Vinci Problem*.

New technologies enable AVs

Although there is much optimism surrounding these enabling technologies, one must acknowledge the considerable uncertainty regarding large scale deployment of fully automated vehicles on urban streets. Many of the optimistic predictions are made by people with a financial interest in the industry, thus overlooking significant hurdles to implementation (Litman, 2018), such as affordability, infrastructure readiness and public acceptance. Yet recent developments in IoT, Sensor technology and LiDAR all have brought the driverless future nearer than ever before.

2.2.2 Sharing

What is Sharing?

The term 'sharing' in the context of transportation can have several connotations, such as ride-sharing or vehicle sharing. Fundamentally this means that a vehicle of any type, which is not privately owned, is run as part of a fleet and used by different users. In this sense, a public bus is as much a sharing model as a car rental. Sharing, like vehicle automation, is not a new concept. Efforts to design and operate an integrated public transport system with on-demand flexibly-routed service have been around for decades (Daganzo, 1978; Wilson and Hendrickson, 1980). However, similar to vehicle automation, integrated demand-responsive transit (DRT) system faced critical challenges due to the constraints of 20th-century technology, such as high costs to operate the service, difficulties to communicate with the riders and manage shared rides, and problems in managing drivers.

Rise of Sharing

Developments in information and communication technology have led to the emergence of transportation network companies (TNCs), such as Uber and Grab. These online communication platforms manage shared rides more efficiently by matching the real-time demand with dynamic fleet operation strategies, thereby lowering the price of the rides (Shen et al., 2018). As a result, there has been a revival of flexible on-demand transit systems, giving rise to concepts such as 'On-demand mobility' or 'Mobility as a Service' (Maas). MaaS typically takes the forms of car-sharing (short-term car rental), ride-sharing (carpooling/vanpooling), ride-sourcing services (or TNCs, such as Uber, Lyft, and Grab), and e-hail services (that use a smartphone app to hail a taxi on-demand electronically) (Greenblatt and Shaheen, 2015). Today some form of MaaS is available in most major urban areas, as shown in the map of various app-based ride-hailing service operators around the world, in Figure 2.3.

The decline of vehicle ownership

As the market share of MaaS platforms grows, we see a decline in private car ownership rates. Figure 2.4 shows that vehicle ownership growth rates started to decline after 1990 in most wealthy European nations. After decades of incline, private car ownership declined in the US for the first time as the percentage of no-car households increased slightly in 2015 (Noyman et al., 2017). Current 18-24 year-olds tend to own fewer cars and drive less than previous generations (Litman, 2015a), as car sharing frees them of the burdens of car maintenance, insurance, and other costs.

MaaS and Automation

Just as MaaS and flexible peer-to-peer carsharing would have been inconceivable without improvements in internet connectivity, reaping all benefits of automation is inconceivable without MaaS. Shared Fully Automated vehicles (SAV) represent an emerging transportation model that offers an opportunity to address many organisational and technological challenges associated with vehicle sharing, such as reducing labour costs, improving compliance, expanding service hours, and improving the spatial and temporal allocation of transport services (Shen et al., 2018). SAVs can be a game-changer in the transportation industry, since they combine the flexibility of 'automobility', without its high carbon emissions, and can even be more cost-effective (Brownell and Kornhauser, 2014). When combined with electrification, SAVs could offer a much more sustainable alternative to the private car.

Figure 2.3 Dominant ride-hailing apps around the world
Tracked in 171 countries around the world in August 2016. Source: SimilarWeb.com

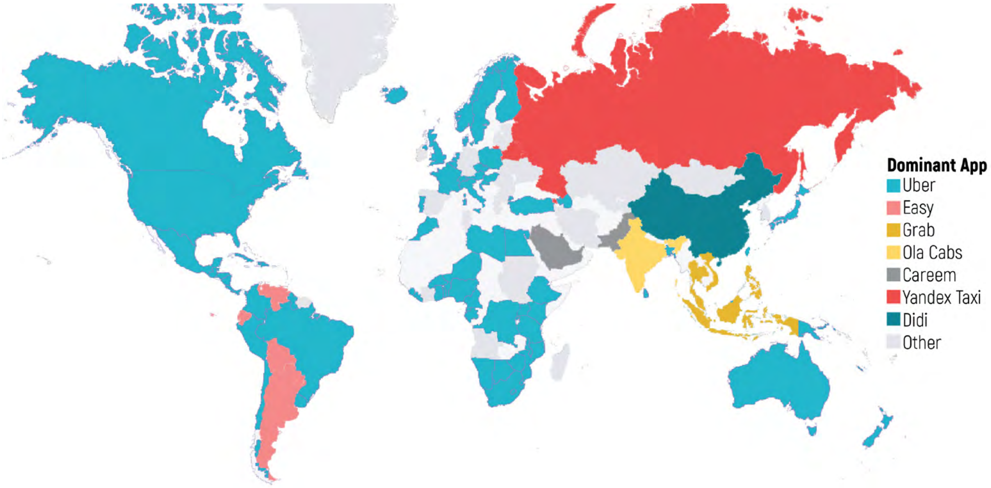
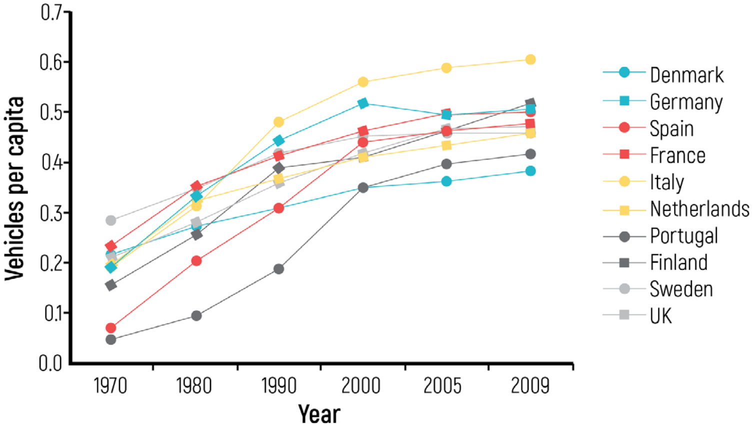


Figure 2.4 International Vehicle Ownership rates
Source: Adapted from (Litman, 2015a)



2.2.3 Electrification

Evolution of EVs

An electric vehicle (EV) uses one or more electric motors or traction motors for propulsion, powered through electricity from off-vehicle sources, with a battery, solar panels or an electric generator. EV technology is almost as old as the private automobile itself. In 1900, about a quarter of all cars in the United States were electric but were quickly overtaken by the internal combustion engine, given the ready availability of cheap fuel. With the recent push towards sustainable transportation, electric vehicles have received renewed attention, with more than 3 million EVs in circulation today (International Energy Agency, 2018). Although vehicle electrification could revolutionise transportation in the long term, it is currently facing many hurdles such as high costs, limited battery range and limited access to charging infrastructure.

How automation and sharing benefits EVs

Development of EV technology is not dependent on automation and MaaS, but is certainly strengthened by it. According to Wadud et al. (2016), highly automated vehicles could travel to alternative fuel stations and refuel unattended, reducing the user's perceived cost and inconvenience. Shared vehicles would add further benefits, due to their high utilisation rates and low operating costs. According to Loeb and Kockelman (2019), the faster the vehicle turnover rates are, the quicker it will lead to the adoption of new technology and a fall in prices of EVs.

Integration of AV and EV

Almost all predictions point to the integration of EV technology with automated vehicles. According to Block and Raustad (2017), it is easier to implement automation features in EVs, since the sensors and advanced computing hardware and software required for automation are more demanding for the car's electrical subsystem. AVs also improve driving efficiency by 5-10%, mitigating anxieties about the range of EVs. Thus electric vehicles form an integral part of the automated vehicle story and the larger technological shift in transportation.

2.2.4 Sensing and Connectivity

What are connected vehicles

Connected Vehicles (CV) refers to the wireless connectivity-enabled vehicles that can communicate with their internal and external environments, such as other vehicles on the street, road infrastructure, and information on the cloud, through various internet and sensing technologies. Lu et al. (2014) refer to these interactions as 'Internet of Vehicles' (IoV), a dynamic mobile communication system that features gathering, sharing, processing, computing, and secure release of information. The rapid development of ICT and IoV is expected to be the next frontier for the automation revolution

Role of connectivity in automated vehicles

The *Da Vinci Problem* in the development of automated vehicles has mostly been overcome by rapid development in sensing technology, ubiquitous connectivity and rise of IoV. Connectivity itself does not imply that the vehicle would be automated, but fully automated vehicles require connectivity. Automated driving systems can use various types of sensors to acquire data about the driving environment and process it internally, but full automation is only truly possible at the convergence of sensor-based technologies and connected vehicle communications (Lutin, 2016). There are three ways in which the connectivity is expected to contribute to the technological shift.

Internet of Vehicles and Places

First is through the development of 'Internet of Vehicles and Places'. US Department of Transportation describes Connected Vehicles as a roadway environment in which wireless communication permits vehicles to communicate autonomously with other vehicles (V2V) and stationary objects such as traffic lights (V2I). V2I requires both vehicles and places, such as homes or public spaces, to be equipped with critical enabling technologies for connectivity. According to Javanshour (2019), these enabling technologies are – LiDAR (an optical remote sensing technology), GPS (a satellite navigation system), DGPS (a more accurate GPS with location accuracy up to 10 cm), RTK (Real Time Kinematics) and Digital maps. When sensors, actuators and virtual information are embedded in vehicles, pavements and traffic lights, information can be exchanged in real-time, creating more efficiency across the transportation network.

Mobile internet

The second way in which connectivity is transforming mobility is through the rise of mobile internet and MaaS platforms based on it. On the consumer end, the rise of mobile internet enables better access to vehicle sharing systems, making mobility as a service more attractive. Consumers have more information for monitoring traffic volumes, delays, arrival times and routing options, making vehicle sharing (and public transport) more reliable and efficient.

Intelligent Transportation Clouds

The third application of connectivity is through Intelligent Transportation Clouds. As vehicles and infrastructure get connected through various IoV technologies, and the users get better connected through mobile internet, we can create, what Javanshour (2019) calls, Intelligent Transportation Clouds. The wealth of data produced and stored on the cloud can provide decision support for policymakers and better traffic management systems. According to Krasniqi and Hajrizi (2016), big data in transportation will transform the automotive industry, marking a shift from the age of products to age of services, where information is the crucial object of value creation.

Death of Distance and Death of Place

Conversely, improvements in connectivity may also pose some threats, as highlighted by a particular branch of transportation literature speculating on the decline of the role of transportation with the increasing virtualisation of life and work. Social media and electronic communication are establishing new lifestyles and habits such as e-commerce and telecommuting, forcing us to question the role of place and transportation, and possible the 'death of distance', a phrase first coined by Cairncross (1997). This phenomenon is only exacerbated by vehicle automation as more and more tasks can be performed in the vehicle.

Little evidence to support the death of distance

The evidence for the death of distance has been, at best, mixed. Rather than substituting for transport, the rise of ICT services in the nineties appears to have contributed to the generation of more physical mobility, producing new forms of physical-virtual mobility (Graham and Marvin, 2001). According to Carroll (2019), places are distinctively significant to people in sheltering, anchoring memories, evoking meanings, and providing a setting for human interactions. It is hard to imagine that Internet of Places and vehicle automation could substitute this.

2.2.5 Tailored Vehicles

Tailored vehicles and streets in fiction

The design of the vehicle itself is evolving in response to new technologies, through tailored vehicles, which are designed for specific types of mobility, occupants, technology integration, or efficiency requirement. Tailored vehicles were commonly seen in futuristic fictional images, such as those in Disney's Magic Highway (Kimball, 1958) shown in Figure 2.5. The vehicles in the image are tailored to fit together like a jigsaw puzzle, create gaps to allow other vehicles to pass through, and deflate and inflate on command. Batmobile is another classic example of a tailored vehicle in fiction, custom-fitted for combat.

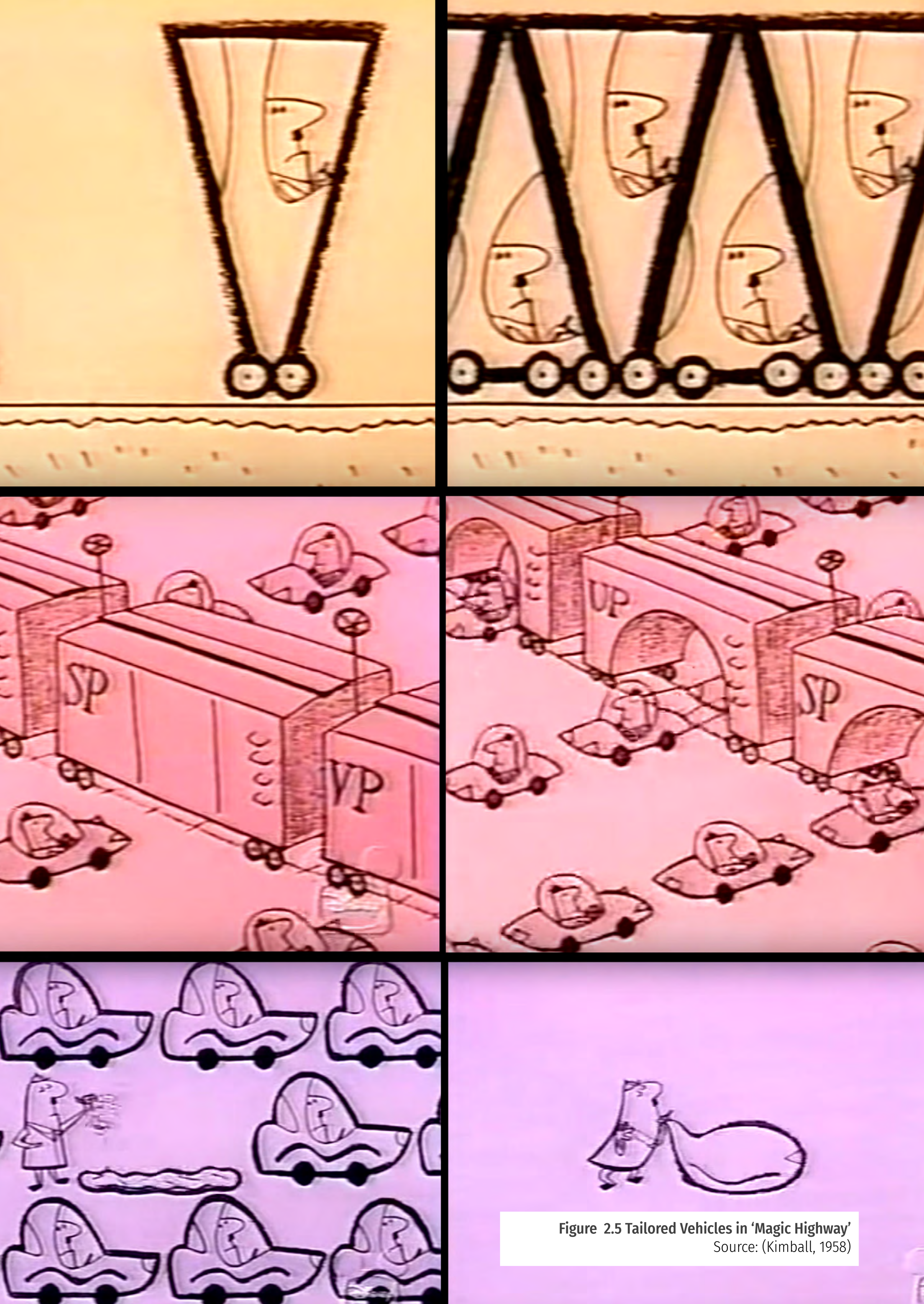


Figure 2.5 Tailored Vehicles in 'Magic Highway'
Source: (Kimball, 1958)

Low-speed multi-use vehicles

Today vehicles are being tailored to respond to vehicle automation, sharing and electrification. Nuro's self-driving delivery bot, shown in Figure 2.6, provides last-mile delivery of local goods and services such as groceries or dry-cleaning. Gelauff et al. (2017) propose *automated taxibots* that may replace buses and trams and Le Vine and Polak (2014) propose *low-speed driverless pods* that can operate alongside pedestrians and cyclists. These vehicles are ideally suited for electric propulsion given that most trips are small range local trips involving one or two passengers. As a consequence, the average size, fuel consumption and capital cost per vehicle will also be much lower than today's average passenger car (Hars, 2015).

Lighter vehicles

The design specifications of all vehicles may also need to be altered to tailor them for vehicle automation. Electrification, fuel efficiency regulations, and safety benefits of automation would render heavy chassis and airbags redundant, making cars smaller and lighter. Since more people will be sharing rides, Wardle (2013) predicts that car fleets will be more mixed and durable. According to Rubinyi (2013), vehicles of a greater variety of sizes, shapes and degree of automation will comingle on the streets in the future. In the future *"the car may just become a tool to get around, and a building a tool to live in, and where the two collide, the boundary between buildings and cars will blur"* (Geoffrey Wardle, 2013), as shown in Figure 2.7.

Figure 2.6 Nuro's self-driving delivery bot delivering groceries
Source: TechCrunch.com

Figure 2.7 A car in 2027
Reimagined by Gabriel Wartofsky Source: (Geoffrey Wardle, 2013) Figure 32b, p.91

3 Impacts of the Technological Shift on Cities

The five technological innovations discussed in the previous section, coalesce to trigger a technological shift in transportation, which will have far-reaching impacts on cities. In this chapter, these impacts are studied through a comprehensive literature review of two types of publications. The first focuses on a limited few outcomes of the technological shift, and use analytical approaches and simulation models to assess isolated impacts quantitatively. These are presented through a review of thirty analytical peer-reviewed studies on isolated impacts. The second are publications that analyse the broader implications of AV, using scenario-based analysis and qualitative methods. Five such holistic scenario studies are reviewed here.

It can be concluded that the technological shift in transportation will significantly alter transportation patterns in the city. The short term impacts of the technological shift are relatively predictable. However, the long term impacts are highly uncertain and dependent on four broad driving forces – the pace of technological development, public acceptance and other social factors, operational policy and regulations, and urban planning and design, which is the focus of this research.

3.1 Studies on isolated impacts

The issue centred approach

Building an accurate model of a complex system like a city and making accurate predictions regarding the impacts of a technology in nascent stages is very difficult. Although the studies on isolated impacts of the technological shift are quantitatively modelled, they can hardly be considered accurate predictive models. Nevertheless, such quantitative studies form the bulk of the literature on the impacts of the technological shift. In this review, a range of existing and potential issues in urban transportation are identified, and the potential impacts of the technological shift in each area is discussed based on a review of quantitative studies.

Existing issues and future concerns

A good starting point to identify potential emerging issues in urban transportation is the Sustainable Urban Development Goals published by the UN in 2018, a blueprint for urban development for the next twenty years. Concerning transportation, the document stresses on access to a safe, affordable, accessible and sustainable transport system for all, particularly for vulnerable users. It also places particular emphasis on the expansion of public transportation (United Nations Department of Economic and Social Affairs, 2018). Among the priority themes related to urban development in the EU's Urban Agenda are the sustainable use of land and sustainable and efficient urban mobility that prioritises public transport, active mobility and equal access (Urban Agenda for the EU, 2018). Singapore's Land Transport Masterplan for 2040 also emphasizes active mobility and public transport (Land Transport Master Plan 2040, 2019).

Five themes of relevance

Five themes of relevance for urban transportation can be identified from these comprehensive documents – traffic flow, space utilisation, energy consumption, impact on transit and active mobility and economic impacts. Thirty peer-reviewed articles published between 2011-19 were selected for this review, as shown in Table 3.1. Each theme is examined separately to understand if the technological shift will alleviate or exacerbate current issues, through evidence found in these thirty studies.

Quantitative methods used in studies

All studies use modelling and simulation as the primary method of analysis. Automated vehicles (AV) are considered in all studies, and half the studies analyse the impacts of shared automated vehicle (SAV), with some degree of connectedness. Four studies specifically look at the impacts of connected automated vehicles (CAV), and three studies also include shared electric AVs (SEAV). Eleven of the simulations are modelled in a hypothetical environment with no corresponding real location. The rest are located in a real-world context, with eight studies in the US, ten in Europe and one in Singapore.

Table 3.1 Thirty studies on the isolated impacts

ID	Study	Location	Method	Tech.
1	(Tientrakool et al., 2011)	No geographic location	Mathematical Modelling	CAV
2	(Burns et al., 2012)	Ann Arbour, Babcock Ranch, Manhattan	Analytical Modelling and Simulations	SEAV
3	(Shladover et al., 2012)	No geographic location	Microscopic Simulation	CAV
4	(Arnaout and Arnaout, 2014)	No geographic location	Microscopic Simulation	CAV
5	(Brown et al., 2014)	No geographic location	Mathematical Modelling	SEAV
6	(Brownell and Kornhauser, 2014)	New Jersey	Mathematical Modelling	SAV
7	(Spieser et al., 2014)	Singapore	Mathematical Modelling	SAV
8	(Childress et al., 2015)	Seattle	Activity-based Simulation	AV
9	(Fernandes and Nunes, 2015)	No geographic location	Agent-based Simulation	CAV
10	(Le Vine et al., 2015)	No geographic location	Microscopic Simulation	AV
11	(Zhang et al., 2015)	No geographic location	Agent-based Simulation	SAV
12	(Ambühl et al., 2016)	No geographic location	Macroscopic Fundamental Diagram and Mesoscopic Traffic Simulation	AV
13	(Fagnant and Kockelman, 2016)	Austin, Texas	Agent-based Simulation	SAV
14	(Friedrich, 2016)	No geographic location	Mathematical Model of Traffic flow	AV
15	(Harper et al., 2016)	United States	Mathematical Analysis	AV
16	(Wadud et al., 2016)	United States	Mathematical Analysis using 'ASIF' Framework	AV
17	(Wagner, 2016)	No geographic location	Microscopic Simulation	AV
18	(Zakharenko, 2016)	No geographic location	Location Choice Modelling	AV
19	(Alonso-Mora et al., 2017)	New York	Mathematical Modelling	SAV
20	(Gelauff et al., 2017)	The Netherlands	Simulations with Dutch Spatial General Equilibrium Model	SAV
21	(Martinez and Viegas, 2017)	Lisbon, Portugal	Agent-based Simulations	SAV
22	(Meyer et al., 2017)	Switzerland	Mathematical Modelling	SAV
23	(Bösch et al., 2018b)	Switzerland	Cost Model	SAV
24	(Bauer et al., 2018)	Manhattan	Agent-based Simulation	SEAV
25	(Bösch et al., 2018b)	Zug, Switzerland	MATSim	SAV
26	(Sinner et al., 2018)	Zug, Switzerland	Cost Model	SAV
27	(Becker et al., 2019)	Zurich	MATSim	SAV + Ebikes
28	(Hörl et al., 2019)	Paris	MATSim	SAV
29	(Hörl et al., 2019)	Zurich	MATSim	SAV
30	(Segui-Gasco et al., 2019)	Greenwich, UK	Agent-based Simulations	SAV

AV: Automated Vehicles; CAV: Connected Automated Vehicles; SAV: Shared Automated Vehicles; SEAV: Shared Electric Automated Vehicles

3.1.1 Traffic flow and value of time

Mobility based paradigm of transportation

Maintaining a smooth traffic flow for the private automobile was initially the single most influential factor in urban transport policymaking. This is defined by Litman (2013a) as the 'mobility-based paradigm' of transportation planning, that focusses on travel distances and speeds. This focus on high traffic flow as a desirable goal began to be questioned as the negative impact of high speed and volume of traffic flow on environmental sustainability, and accessibility became evident.

High mobility is important despite social costs

There exists a contradiction between the desire to speed up and the desire to slow down traffic (Banister, 2008). We seek to minimise the time lost in congestion while minimising social costs of high mobility through transport policy. At the same time, a certain level of congestion is now considered 'desirable' in some locations such as residential streets. In urban studies literature, the humanist figure of the pedestrian is favoured over cars which are seen as the enemy of urbanity. Despite its social costs, high mobility remains desirable. According to Sheller and Urry (2000), mobility is in some ways a democratic right, and both urbanisation and *automobilisation* are together characteristic of the culture of cities. "*However much we despair of vehicular traffic and busy roads, the auto-freedom of movement is what can constitute democratic life.*" (Sheller and Urry, 2000).

Will the technological shift augment or curtail traffic flow?

Opposing viewpoints

Studies on the impact of the technological shift on traffic flow present two opposing points of view. The first viewpoint suggests that there will be significant improvements in traffic flow as the technological shift enables more efficient driving and intelligent management of modes. In another view, these gains may be cancelled out due to addition of new induced and latent travel demand, change in the value of travel time and increased detours by shared vehicles.

Gains from efficient driving

Automated vehicles drive more efficiently at higher speeds and a shorter minimum headway, that may result in a reduction in congestion. Wagner (2016) demonstrates through traffic simulation studies that autonomous systems reduce intersection delays by 5-80%, with an average value of 40%. According to this study, it may be asserted with confidence that in the urban context, the introduction of AVs has the potential to generate substantial time gains at traffic signals. However, a microscopic traffic simulation by Arnaout and Arnaout (2014) suggests that these gains are not significant under a low to moderate penetration rate of AVs. For noticeable gains in traffic flow, at least 40% of all vehicles on the street need to be automated. Additionally, if the AV has to deliver similar rider comfort as today, it needs to accelerate and decelerate considerably slower than conventional vehicles, which can even reduce traffic flow from current levels (Le Vine et al., 2015).

Intersection capacity benefits due to connectedness

The throughput of traffic at intersections can also improve dramatically with CAVs. Friedrich (2016) considers the gains from automation on signalised intersections in his mathematical model of traffic flow. In current traffic conditions where vehicles are exclusively controlled by humans, the intersection capacity is about 800 cars/h per lane. With 100% automated traffic, the capacity would increase to about 1120 cars/h per lane, a 40% increase, due to better reaction time. Tachet et al. (2016) replace traditional traffic lights with 'slot-based intersections' (SI) in a microscopic traffic simulation. They theoretically show that transitioning from a traffic light system to SI has the potential to double capacity at an intersection and significantly reduce delays. However, these SI simulations have been criticised for ignoring pedestrian and cyclist flow at intersections (Eric Jaffe, 2015).

Gains from vehicle sharing – fewer vehicles

Shared vehicles may further reduce travel time since fewer vehicles are required on the street to serve the same number of trips. For example, according to a simulation study, a fleet of 9000 vehicles can serve all taxi trips in Manhattan with an average waiting time of less than a minute (Burns et al., 2012). Bauer et al. (2018) use agent-based simulations for shared electric AV Taxis in Manhattan and arrive at a fleet size of 6470 vehicles. This number is smaller than the previous study even though the simulation takes into account the extra time required for vehicle charging which could be because the waiting time for the ride can be up to 10 minutes. Several other studies find a similar reduction in overall fleet size for Shared Automated Vehicles (SAV) in different operational contexts (Alonso-Mora et al., 2017; Fagnant and Kockelman, 2016; Spieser et al., 2014), but the magnitude of improvement is subject to various external planning and operational policy decisions.

Gains from vehicle sharing – better network performance

With reduced congestion on the street, the average total service time for shared vehicles may improve, even if we factor in the detour, waiting, pick up and drop off time, as demonstrated by an agent-based simulation study of SAV deployment in Austin, Texas (Fagnant and Kockelman, 2016). Agent-based simulations of SAVs in Greenwich, UK finds travel time reduction of up to 41% due to vehicle sharing and automation (Segui-Gasco et al., 2019). A study of SAVs deployed in Zurich area suggests that maximum speeds remain higher for private vehicles compared to pooled vehicles (Becker et al., 2019). However, a substantial improvement in network performance is seen overall (up to double the speed), due to capacity benefits of automation and more efficient use of pooled vehicles.

Change in value of travel time

An interesting effect of vehicle automation is the change in the value of in-vehicle travel time, defined by the cost of time spent in commute. Vehicle automation will allow the user to spend a large portion of in-vehicle time productively engaged in other activities, resembling the in-vehicle experience of a transit passenger on a bus or train. Transit passengers are less sensitive to changes in travel time than automobile drivers (Litman, 2012; Zhang and Timmermans, 2010), and can use in-vehicle time more productively in the information age (Lyons and Urry, 2005). In a more radical vision of the future with automated vehicles, *"time slots that were previously almost exclusively occupied by travel will dissolve into permeable channels of flows permitting overlapping continuity of activities"* (Malokin et al., 2015).

Travel time losses due to detours

In an opposing viewpoint, shared vehicles may also act as moving bottlenecks (when stopping to allow passengers to board or alight) and induce higher vehicle kilometres travelled (VKT) through detours and empty travel (Becker et al., 2019). According to an activity-based model of Seattle, speed and capacity increases may improve regional mobility, but they could also induce additional demand leading to more VKT, and hence higher greenhouse gas emissions (Childress et al., 2015). In their New York-based study, Alonso-Mora et al. (2017) observe that there could be delays due to detour, higher waiting times and more VKT, contradictory to the Austin study (Fagnant and Kockelman, 2016), depending on the size and capacity of SAV fleet. Smaller fleet size, larger capacity and longer waiting/delay times increase the possibilities for ride-sharing, thus increasing the mean vehicle occupancy.

Travel time losses due to induced and latent demand

Reduced perceived travel time, and change in the value of travel time, may create new induced demand. According to a study of SAV implementation in Switzerland, the additional demand generated outweighs the capacity benefits or automation, and would lead to substantial increases in travel times (Meyer et al., 2017). Newly mobile population enabled by automation, such as children, elderly and the disabled, constitute a latent demand which may add to this induced demand. A mathematical modelling study estimates that increased travel under this effect could reach up to 40% in the US (Brown et al., 2014).

3.1.2 Space use and consumption

Private cars are too space intensive for high-density Asian cities

The spatial imprint of transportation infrastructure can be quite substantial. In high-density Asian cities, space is a valuable commodity, and if fast-growing cities have to accommodate both high mobility and large population, they need to move away from the private automobile. Even if we factor in space gains from automation and building vertical/underground, private cars are too space-intensive. The growth of car ownership outpaces the growth of road capacity in most urban areas around the world, forcing planners to consider a new mix of policy instruments to maintain minimum service standards in the face of further increasing congestion (Axhausen and Gärling, 1992).

Large spatial imprint is detrimental to urban vitality, sustainability

The large spatial imprint of transport flows also endangers urban vitality. Urban sprawl and suburban development are directly linked with the growth in the private automobile sector. A large urban footprint is considered environmentally unsustainable since longer travel distances lower accessibility and increase VKT. Since changes in transportation technology alters urban form (discussed in greater detail in section 5.5), the impacts of the technological shift on space use and consumption needs to be investigated.

Will the technological shift increase or decrease the spatial imprint of urban transportation?

Better space utilisation – lateral, longitudinal

One of the direct benefits of vehicle automation is a better utilisation of road space – both lateral and longitudinal (Sperling, 2018). Lateral space can be gained by narrowing lane widths to as low as 2.5 meters (Schlossberg et al., 2018), from the current standard of 3.2-3.7 meters, since AVs can drive more precisely. Longitudinal space can be gained by reducing the gap between vehicles. Humans should not drive with a gap of less than 0.9 s, and the legal recommendation is 2 s, whereas an AV can drive with a 0.3-0.5 s gap, leading to more efficient use of longitudinal space (Wagner, 2016).

Longitudinal capacity gains can lead to induced demand

The longitudinal gains in road capacity depend on road type and changes in demand. A mathematical model of the flow of purely autonomous traffic shows that street capacity can increase from 40% to 80% depending on the type of street (Friedrich, 2016). Ambühl et al. (2016) also find that road space needed can decrease by around 11-12% only as a result of automation, serving the same number of trips. However, they also find that if the same road infrastructure is maintained, the total number of trips may potentially triple. Thus, excess road space provision can also lead to induced demand.

Road capacity benefits from connectedness

Further longitudinal capacity benefits can be drawn from CAVs. Tientrakool et al. (2011) show that AVs equipped with sensors can increase highway capacity by 43%, and those equipped with cooperative adaptive cruise control (CACC) can increase highway capacity by 273%. It can be concluded that connected automated vehicles offer much more substantial gains in terms of road capacity than only AVs. However, these gains are contingent on the market penetration of the technology and the street type (Shladover et al., 2012). Connected vehicles can also dramatically increase intersection capacity as discussed previously, rendering traffic signals obsolete and freeing up space at intersections.

Vehicle sharing leads to less road space consumption

Vehicle sharing may lead to fewer vehicles on the street overall, resulting in further increase in longitudinal capacity. In all three simulation models of Ann Arbour, Babcock Ranch and Manhattan, Burns et al. (2012) found that far fewer shared cars were needed to serve the same number of trips as privately owned vehicles. Alonso-Mora et al. (2017), Fagnant and Kockelman's (2016) and Spieser et al. (2014) also reach the same conclusion from their studies in New York, Austin and Singapore respectively. Hörl et al. (2019b) find that the fleet size required to serve all trips originating and ending in Zurich city could vary between 7000 to 14000, depending on the choice of operational policy, e.g. customer vehicle assignment, repositioning of empty vehicles, costs etc.

Benefits from Platooning

Another mechanism through which longitudinal space benefits can be gained is vehicle 'platooning'. Platooning refers to the practice of multiple vehicles following one another closely, leading to reductions in aerodynamic drag for all of the vehicles. Fernandes and Nunes (2015) find that platooning may increase road capacity by almost five times, based on agent-based simulations. However, these capacity benefits may not be entirely realised since the complex, unpredictable movements of city traffic, cyclists and pedestrians, can make platooning difficult.

Problems with platooning

In order to create efficient platoons, they need to be entirely separated from the rest of the traffic, through barriers or grade separation (Litman, 2018). Such a dedicated infrastructure may be costly to build and could fragment the urban fabric. Even if the longitudinal capacity benefits from automation, sharing and platooning are entirely realised, it would be challenging to remove selective portions of roads based on these results, without creating bottlenecks. The platoons themselves may function as moving bottlenecks in mixed traffic flow.

Better parking utilisation

The space required for parking can be significantly reduced through changes in parking infrastructure design for automated vehicles. Nourinejad et al. (2018) use numerical modelling to test optimal parking layout for AVs and find that AV car-parks can decrease the need for parking space by an average of 62% and a maximum of 87%. As we move towards greater vehicle sharing, parking requirements would reduce even further. Currently, multiple parking spaces are required for a single private vehicle – at home, work and other activity spaces. Agent-based simulations of Greenwich show that automated mobility on demand can reduce parking space requirement by 16-38% due to reduction in trips that require parking (Segui-Gasco et al., 2019). Zhang et al. (2015) use agent-based simulations show a 90% reduction in parking demand if all trips are conducted by shared autonomous vehicles. The freed up space from streets and parking (both in structures and on-street), will offer new redevelopment opportunities, which can be used densify city centres and build additional infrastructure for active mobility.

Location choice – urbanisation vs sub-urbanisation

The technological shift will have a substantial impact on the overall footprint of the city, by influencing work and home location choices in the long term. Gelauff et al. (2017) use simulations of a spatial general equilibrium model (LUCA) in the Dutch context and conclude that AVs could induce both urban dispersion and concentration effects. Dispersion of population in suburban areas resulted when more productive use of car travel time was assumed in the model. A concentration of population resulted when most public transport services (i.e. bus, trams, metro) were replaced by door-to-door shared automated mobility services. Zakharenko (2016) built a location choice model to study the impact of vehicle automation and found a 7.1% increase in the urban land area. He observes an overall increase in the number of commuters, and therefore parking demand, and decrease in parking space requirement due to more efficient use of parking space, leading to a net increase in parking space by 7.4%. The willingness to travel longer distances due to increased value of travel time could increase the urban footprint, cancelling out the gains in longitudinal capacity.

Conclusion

As this review shows, AVs can both increase or decrease road capacity, parking space requirement and urban footprint, depending on transport policy, urban planning, prevailing local conditions and operating model (Faisal et al., 2019). Space benefits can be maximised only when the connected and shared mobility is fully embraced, and vehicle automation reaches significant market penetration rates.

3.1.3 Energy consumption

Road transportation has high energy impact

Transport is arguably the single biggest issue for environmental debates relating to urban form (Jabareen, 2006). Road transportation alone consumes on average, 85% of the total energy used by the transport sector in developed countries (Rodrigue et al., 2013). Policies for sustainable urban development are strongly tied together with transportation policies. In recent years as climate change related issued gain traction, the emphasis has shifted to sustainable transportation policies (Banister, 2005), with the objective to reduce the need to travel, promote energy-efficient transport modes, reduce emissions, improve the safety of pedestrians and improve the attractiveness of cities. The ongoing technological shift is expected to contribute significantly to the goals of sustainable transportation.

Will the technological shift increase or decrease overall emissions due to road transportation?

Eco-driving effects

This theme lends itself best to quantitative analysis and several computational models have been built to predict the environmental impacts of the technological shift in transportation. Automation technology is expected to improve fuel economy through *'eco-driving'* which includes a set of practices that can decrease fuel consumption, without any changes in vehicle design. For example, driving at moderate speeds to yields best engine efficiency by minimising braking and acceleration cycles. Wadud et al. (2016) find a reduction in energy consumption between 5–20%, due to eco-driving, and Brown et al. (2014) find a reduction of 10% due to the same effect, depending on the initial level of congestion. On the other hand, in order to save time, vehicles may drive at a much higher speed than today which could lead to an even higher fuel consumption than today, with an increase of 7-22% for light-duty vehicles on highways (Wadud et al., 2016).

Platooning effects

Platooning is another mechanism through which energy consumption can be reduced. As vehicles drive in tightly packed platoons, the aerodynamic drag is reduced. The longer the platoon, the more the drag reduction and hence energy saving. Wadud et al. (2016) find that if platooning were universally adopted on highways by light-duty vehicles, energy consumption may reduce by 3-25%. Brown et al. (2014) estimate these reduction effects to be around 10%. However, the real benefits of platooning cannot be realised unless stopping and braking instances are minimised, and the length of the platoon is maximised, which could be hinder active mobility flows.

Electric vehicle effects

The impact of vehicle electrification on emissions is generally very positive. In an agent-based modelling study of Manhattan, a shared automated electric vehicle (SAEV) fleet deployed to replace all traditional taxis, resulted in significantly lesser emissions. When we compare the combined effect of electrification and vehicle sharing, with personal electric vehicles serving the same number of trips, the GHG emissions can be reduced by more than half. Connected vehicles will also be better routed, selecting the most efficient route to avoid traffic, reducing energy consumption by up to 5% (Brown et al., 2014). An agent-based simulation of Manhattan shows that replacing personal vehicles with short-range SEAVs could reduce GHG emissions by more than half (Bauer et al., 2018).

Tailored and Connected vehicle effects

Tailored vehicles are another mechanism to reduce fuel consumption. A self-driving car is expected to be much safer than a human-driven one, which may eventually lead to a smaller and lighter vehicles. A tailored vehicle that can potentially shed the extra weight of safety equipment would lead to a reduction of about 5% in fuel consumption according to a study (Wadud et al., 2016). These vehicles can be further 'right-sized' given increased vehicle sharing and better utilisation of vehicle fleet. For example, average usage times of private cars in Switzerland per day is 1.32 h, but according to a simulation of SAVs in Zurich, vehicle utilization could increase by a factor of 2 to 7 when shared vehicles are introduced, irrespective of the fleet size (Hörl et al., 2019). Similarly, Martinez and Viegas (2017) find that vehicles are used much more intensely, from approximately 50 min per day today, to 12 hours per day, in an agent-based simulation of SAVs in Lisbon. High intensity of use reduces the operating life-cycles, allowing quicker renewal of fleets resulting in a younger and environmentally cleaner fleet.

Vehicle sharing benefits

An obvious benefit of vehicle sharing and more intensive use of every vehicle is the reduction in the overall vehicle kilometres travelled, which can be taken as a proxy for emissions. According to an agent-based simulation of Lisbon, if all private vehicles and bus services were to be replaced by shared AVs, carbon emissions would reduce by almost 40% in the most favourable scenario. (Martinez and Viegas, 2017). In a simulation of Zug, Bösch et al. (2018b) find a 12.4% change in mode share, switching from private cars to automated taxis, reducing the overall number of vehicles.

Caveats to gains from vehicle sharing

However, there are some caveats to these gains from vehicle sharing. Becker et al. (2019) simulate SAVs in Zurich and find that ride-hailing increases energy consumption by competing with transit and active mobility. They suggest that making agents consider the social cost of their car trip can help to reduce transport-related energy consumption by almost 25%. A similar suggestion is made by Childress et al. (2015), based on an activity-based model of Seattle. They find that if self-driving cars are priced per mile, VKT could be reduced, by as much as 20%. Fagnant and Kockelman (2016) also observe an overall reduction in VKT in their simulation study of Austin, contingent on a greater emphasis on ride-sharing. Thus pricing and operational policy are a key determinant in determining the environmental impacts of SAVs.

More VKT due to mode shift, empty rides

Some studies predict an increase in VKT with SAV implementation contrary to previously discussed results. This increase comes from empty rides and changes in mode choice. According to a study, an upper bound of a 14% increase in annual VKT is found, for the US population 19 and older due to added demand of the non-driving elderly and people with travel-restrictive medical conditions (Harper et al., 2016). In Spieser et al. (2014) simulation study of Singapore, although shared AVs provide mobility to the entire population with far fewer vehicles, these vehicles also end up travelling more. In the agent-based simulation of Greenwich, Segui-Gasco et al. (2019) observe that the total number of vehicle kilometres driven by the shared AV fleet increases by 57%, leading to a 24% increase in carbon emissions.

Similarly, Ambühl et al. (2016) find that although vehicle automation can reduce road space required by 11-12%, if the given road infrastructure remains as is, it may triple the total number of trips due to induced demand.

Induced and latent demand

The impact of the addition of latent demand and induced demand on emissions can be significant, and may even eclipse the gains from eco-driving and electrification. According to a location choice modelling study by Zakharenko (2016), even though the urban footprint area increases by 7%, increasing the traffic, the overall congestion may not increase since AVs are expected to operate more efficiently. On the other hand, according to an agent-based simulation of Greenwich, although travel times for private car users are reduced by 4%, emissions increase by 24% because of the overall increase in distances driven.

Uncertainty in overall impacts

When all these effects are taken into consideration, the overall impacts can be uncertain. Brown et al. (2014), summarise the combination of all these effects in Table 3.2. From the agent-based simulation of Zug, Bösch et al. conclude that vehicle automation could reduce energy use and greenhouse gas emissions in half in an optimistic scenario or double them in a 'dystopian nightmare'. It is clear that vehicle automation does not automatically result in reductions in energy consumption and emissions, but it indirectly supports changes in vehicle operations, vehicle design, choice of energy, policy intervention, or transportation system design that may or may not be more sustainable.

3.1.4 Transit and active mobility

Benefits of transit

Walking, cycling, public transport, including buses, trams, trains all add to the vitality and diversity of transport flows in cities. The primary benefit of public transit is the efficiency built into it – transporting the maximum number of people using minimum energy and space resources. It also contributes to the vitality of the city by encouraging chance encounters, with 'familiar strangers' (Sun et al., 2013). A well-designed transit policy can be a useful instrument for social justice and transport equity (Lucas, 2006). Literature can be found on the many benefits of public transit for better public health (Litman, 2013b), climate change mitigation (Kwan and Hashim, 2016), efficiency and equity (Litman, 2015b).

Benefits of active mobility

Active mobility is a collective classification of walking and cycling. It is not only environmentally friendly but contributes to the vitality of a city and the health of its populace. Pedestrians are the 'eyes on the street' (Jacobs, 1961), that create a sense of safety and community. Transit ridership also depends heavily on high-quality pedestrian environments. At the same time, pedestrians are also the most vulnerable users of the street, especially so in car-oriented developments.

Threats to transit and active mobility

The noise and fumes generated by high-speed vehicular traffic make walking unpleasant and unsafe. Massive road infrastructure can create a rupturing effect in communities, as in the case of highways cutting through neighbourhoods. The biggest threat to transit also comes from the private automobile, which has contributed to the decline in public transit ridership in many cities. According to Urry (2004), public transport rarely provides the seamlessness and flexibility of a personal automobile, and thus cannot compete with it.

Table 3.2 Summary of Vehicle effects on Energy consumption

Effect	**Approach**	**Effect Estimate**
(a) Platooning: close following at high speed to reduce drag	Use estimates of overall savings potential from literature	−10 %
(b) Efficient driving: smooth start-stop, some stop elimination	Use estimates of eco-driving potential	−15 %
(c) Efficient routing: traffic avoidance and most efficient route selection	Example cases from Buffalo, NY and collaborative Chevy Volt project	−5 %
(d) Travel by underserved populations: (youth, disabled, and elderly)	Estimate the additional miles if all people over 16 had the VMT of the highest demographic	+40 %
(e) Efficient driving (additional): full stop elimination and trip smoothing	Use upper bound of efficiency improvement from smooth travel	−30 %
(f) Faster travel: possible due to safe highway operation	Estimate impact on fuel economy from aerodynamic drag at 100 mph	+30 %
(g) More travel: due to faster travel and reduced traffic, people may live farther from destinations or travel more	Assume the current time spent travelling remains the same (so miles increase with speed)	+50 %
(h) Lighter vehicles and powertrain/ vehicle size optimization: Very few crashes and smoothed driving could enable light vehicles with small powertrains for many duty cycles	Assume weight could be reduced ~75 % and each 10 % reduction = 6–8 % reduction	−50%
(i) Less time looking for parking: from fewer vehicles and self-parking	Assume it cuts the wasted fuel in half	−4 %
(j) Higher occupancy: facilitated by IT, automated carpooling	Use the upper bound estimates for “dynamic ride-sharing”	−12 %
(k) Electrification: deployed vehicle could be matched to user trip need	Estimate the share of vehicle trips that could be met with a 40 mi electrified range	−75 %

Source: Adapted from (Brown et al., 2014) Table 1, p. 141

Outlook

The relationship between transit and active mobility is not as contentious. Good transit infrastructure generally supports active mobility and vice versa since virtually every transit rider is also a pedestrian. Cities such as Amsterdam, Stockholm, Portland, Singapore have developed explicit policies to upgrade and prioritize cycle lanes and public transport, in order to draw people away from private vehicles. Just as the private automobile impaired transit and active mobility, concerns are emerging regarding how they would be impacted by the technological shift in transportation.

Will the technological shift threaten transit and active mobility or strengthen it?

Vehicle sharing will improve transit access

Transit cannot compete with the flexibility of the automobility system, but shared automated vehicles offer the possibility to close the gap between traditional fixed-route transit and the private automobile. They facilitate flexibility in the time of arrival, offering different levels of privacy, route options and vehicle size options. In an agent-based simulation of Lisbon with only rail-based transport and shared taxi (4 – 16 seater) as transport options, a vast improvement in access to jobs for public transit users was observed (Martinez and Viegas, 2017). Meyer et al. (2017) also find gains in accessibility in their model of SAV deployment in Switzerland. However, these gain are distributed unevenly. While rural areas experience significant gains, in the larger cities, the additional demand outweighs the capacity benefits leading to an increase in travel times and therefore lower accessibilities.

Vehicle sharing may decrease traditional transit ridership

SAVs can provide similar levels of access as a private car to everyone, depending on the urban context of operation, but they may *also* reduce the ridership of traditional transit. In agent-based simulations of shared automated mobility-on-demand in Greenwich, although private car use reduced by 6-15%, bus trips are also reduced by 8-34%. (Segui-Gasco et al., 2019). Becker et al. (2019) simulated SAVs and shared e-bike in Zurich and observe that the presence of small car-sharing and ride-hailing fleets increase the demand for bike-sharing, whereas competition by large car-sharing fleets reduces it. In contrast, the presence of a small bike-sharing schemes lowers the demand for car-sharing, but larger bike fleets increase it. These conclusions highlight the potential threat from new services to core public transport patronage and active mobility.

People may switch from active mobility to AV

Most studies in the area of active mobility and automated vehicles focus on the behavioural interaction aspects. A collection of such studies is summarised by Rasouli and Tsotos (2018). Speculations on the impacts of the technological shift on active mobility mode shares are mostly made based on interviews and surveys. Booth et al. (2019) conducted an online survey of 1624 Australians of driving age and found that a significant number of respondents would be likely to use AVs instead of walking (18%), cycling (32%), and public transport (48%). Alessandrini et al. (2015) speculate that vehicle automation should efficiently integrate cars with non-motorised modes of transport like walking and cycling, reducing intimidation by cars, based on a Delphi survey.

Crosswalk chicken

In another view, AVs and pedestrians are considered fundamentally incompatible. Millard-Ball (2016) uses game theory to analyse the interactions between pedestrians and AV and finds that pedestrians can behave with impunity since AVs are more risk-averse than human drivers. He calls this the game of ‘crosswalk chicken’, where pedestrians may be more inclined to jaywalk since AVs drive more carefully, thus slowing down the automated vehicle. There could be two ways to deal with this problem - a shift towards pedestrian-oriented urban neighbourhoods, or sidewalks and crossings with physical barriers between pedestrians and AVs. While in the former case the benefits of automation can hardly be realised, in the latter case the splintering effect of transport infrastructure is furthered.

3.1.5 Economic affordability

Need for affordability

If the freedom of mobility is a universal right, affordable transport services are the key to maintaining this right. Pricing affects what transportation service, and consequently, what destinations and activities, can be accessed by most people. In transportation, there is a sharp contrast between the direct individual advantages for many, and the indirect long-term disadvantages for the society as a whole, making it a so-called social dilemma (Rooij, 2005). Who pays for the cost of mobility?

Cost of mobility

Public transit infrastructure is expensive to build and run and is heavily subsidised in most cities. Martens (2016) raises multiple questions regarding this: Should all travellers pay full costs of their journey or should travel be subsidised? Is it justified to subsidise public transport but have car users pay full price? Are car users paying full price, including the ‘social costs’ of driving (Boarnet and Crane, 2001)? The technological shift raises another question regarding how the reduction in operating costs of vehicles may impact the social costs of mobility.

Will the technological shift increase or decrease the cost of mobility?

Reduction in investment for road infrastructure

An unresolved aspect of the technological shift is, who pays for the roads? (Sperling, 2018) Taxes, fees and tolls from private automobile users contribute significantly to road construction budgets. Loss of this revenue stream, combined with the loss of revenue from parking is a matter of concern for transportation authorities. This loss of revenue may be supplemented by the reduction in proposed road expansion investments as platooning and eco-driving could increase road capacity by as much as five times (Fernandes and Nunes, 2015).

Fuel savings due to automation

Although AV technologies may raise the initial purchase price of a vehicle, reduction in operating cost through lower insurance fees, maintenance and reduced fuel costs due to eco-driving, may balance this out. However, according to Brown et al. (2014), fuel costs may also increase due to an increase in the overall number of kilometres driven as a result of induced demand. To counter this, Childress et al. (2015) test pricing of self-driving cars per mile, in an activity-based model of Seattle. Both vehicle kilometres travelled and vehicle hours travelled could be significantly reduced, by as much as 20 and 30%, respectively, with transit shares almost doubling.

Fuel savings due to automation

Shared AV implementations are expected to result in further cost benefit by eliminating the cost of drivers. According to a detailed cost model of Switzerland, autonomous driving technology allows taxi services and buses to operate at a substantially lower cost, even cheaper than private cars. In relative terms, automated taxis will be only 71% more expensive for an individual, and 21% more expensive for pooled use than automated buses (compared to 415% and 204% before automation) (Bösch et al., 2018a). According to a cost model of Shared AV implementation in Zug built by Sinner et al. (2018), the operating costs of bus networks can be reduced by 50% to 60% through automation. A simulation of SAVs in Paris shows an operating cost of 0.27 EUR/km, which is lower than the full cost of owning a private vehicle (Hörl et al., 2019).

Additional parameters to be considered – electrification

On the contrary, a simulation of SAVs in Zurich shows an operating cost of 0.4 CHF/km under ideal conditions (highest possible demand, free-flow speeds). This price cannot compete with conventional public transport or private cars in the short term. Trade-offs between monetary travel costs, the value of time and customer acceptance, as well as additional parameters such as investment, maintenance cost and fleet size, need to be explored. For example, increasing battery range, charging speed, and the density of chargers can decrease the number of vehicles required but also increases other costs. In an agent-based simulation of Manhattan, the estimated cost for the operation of an SEAV fleet is roughly ten times lower than a regular taxi fare, as a result of savings due to electrification, the elimination of driver cost and efficiency of a single-operator, smartphone-based system (Bauer et al., 2018).

Impact on land prices

One unexpected outcome of vehicle automation could be inequity in real estate values. According to simulations of the Dutch Spatial General Equilibrium Model, car automation alone will result in population flight from cities and convergence of residential prices between cities and rural areas. However, public transport automation has the opposite effect. It leads to further population clustering in urban areas, and an increase in residential price disparity between cities and rural areas (Gelauff et al., 2017). Thus several factors need to be considered to accurately predict the long term economic impact of the technological shift.

3.1.6 Summary of Impacts

Table 3.3 Threats and benefits of the technological shift in transportation

Themes	Potentials Benefits	Potential Threats
Traffic flow and value of time	Improvement in traffic flow due to more efficiently driven automated vehicles (17), and techniques such as platooning (9). Increased throughput at intersections (14). Better network performance and fewer vehicles on the street due to vehicle sharing (2) (7) (13) (19) (24). Change in value of travel time as in-vehicle time is utilised more productively (8). Travel time improvements with vehicle sharing, despite detours and access/egress time (13) (27) (30).	Doubts about whether capacity benefits can be realised while maintaining a certain level of user comfort (10). Increased congestion due to the addition of latent demand (5). Induced travel demand due to the change in the value of travel time (8). Improvements in traffic flow are subject to existing traffic conditions and the penetration rate of the technology (4). Additional travel time may be required due to detours in shared vehicles (19) and induced demand (22).
Space Use and Consumption	Lateral and longitudinal street capacity gains due to fewer vehicles on the street (2) (7) (13) (14) (17) (19) (29), more efficient driving and platooning (1) (3) (5) (9) (12) (14) (16). Better utilisation of transport infrastructure such as parking (30) (11). SAV could lead to 'concentration effects' in urban development (20).	May lead to more sprawling and suburbanisation (18) (20). AVs may move slower than human-driven vehicles, leading to a decrease in capacity (10). Increase in commuting due to induced demand may lead to higher parking demand (18). Overall number of vehicles in the system depends on the efficiency of the vehicle charging system (24).
Energy consumption	Increase in carsharing will reduce energy consumption (24) (27), through more efficient driving (18) (21), and fewer VKT (5) (8) (13) (25). Vehicle utilisation would be better, allowing for quick renewal of fleet, remaining more fuel-efficient (21).	Ride-hailing may have a negative impact on energy consumption, if it competes with public transit and active mobility (25) (27). Increase in VKT due to addition of latent demand and induced demand may lead to higher energy consumption (7) (12) (15) (16) (30).
Transit and Active mobility	Despite vehicle waiting times and detours, shared vehicles can provide high level of service, reduce overall travel times (2) (13) (27) (30) and improve transit accessibility (21) (22).	AV's may cannibalise the mode shares of traditional transit (30). Increase in size of car sharing fleet may reduce demand for bicycle sharing (27).
Economic Affordability	Initial purchase price of AVs may be higher (25) but the operating cost of shared vehicles and taxis would be lower (2) (13) (24) (23) (26). Initial purchase price of shared AVs may be lower since fewer vehicles are required to serve the same number of trips (2) (6) (7) (13) (19). Cost of hiring shared vehicles would be less than owning an AV, reducing private vehicle ownership rates (28).	Absolute cost difference between buses and private taxis may reduce substantially (25), reducing public transit mode shares. Other costs such as charging speed, and the density of chargers can decrease the number of vehicles required but also increases other costs (24). May result in population dispersion, greater disparity in real estate values (20). Fuel costs may increase or decrease depending on driving efficiency vs. induced demand (5).

The numbers in brackets indicate the serial number of papers referenced, given in Table 3.1

3.2 Review of holistic visions and scenarios

About Scenarios

The second set of publications reviewed here investigate the broader implications of the technological shift in transportation, using scenario-based analytical approaches. This method, which falls within the class of conjectural forecasting methods, is frequently associated with future research. Scenarios tend to be collectively authored and described as narrative texts or diagrams. There are many definitions of scenario planning – 'a view of what the future might be', 'tools for managing uncertainties of the future', a 'disciplined methodology for imagining possible futures' (Amer et al., 2013) and as 'design in itself, due to its communicative, projective, transdisciplinary and generative nature' (Jonas, 2001). The methodologies used to construct scenarios also vary greatly.

Five scenario-based studies on the technological shift in transportation are reviewed here in three steps – a discussion on how the scenarios are constructed, followed by a description of the scenarios, ending with an analysis of how these scenarios fare on the five themes discussed before.

3.2.1 Scenario construction methodology

The five selected studies use different methods to construct 3-4 scenarios, as shown in Table 3.4. Gruel and Stanford (2016) and Milakis et al. (2017b) conducted interviews and workshops with external experts, while Meyboom (2018) and Townsend (2014) conducted internal brainstorming sessions and literature review. Heinrichs (2016) used systematic literature review as a method to construct his scenarios.

The 'Shell approach' of scenario construction

Both Study (4) and Study (5) use a modified 'Shell approach', also known as 'intuitive logics approach', as a method for scenario construction. This approach was first used by Pierre Wack and his colleagues at Royal Dutch Shell. It begins with the base assumption that decisions are based on a complex set of relationships among the economic, political, technological, social, resource, and environmental factors. A hypothetical sequence of events is constructed to focus attention on causal processes and decision-points (Amer et al., 2013). Both studies (4) and (5) follow four steps to construct the scenarios.

Identifying and ranking drivers by impact and uncertainty

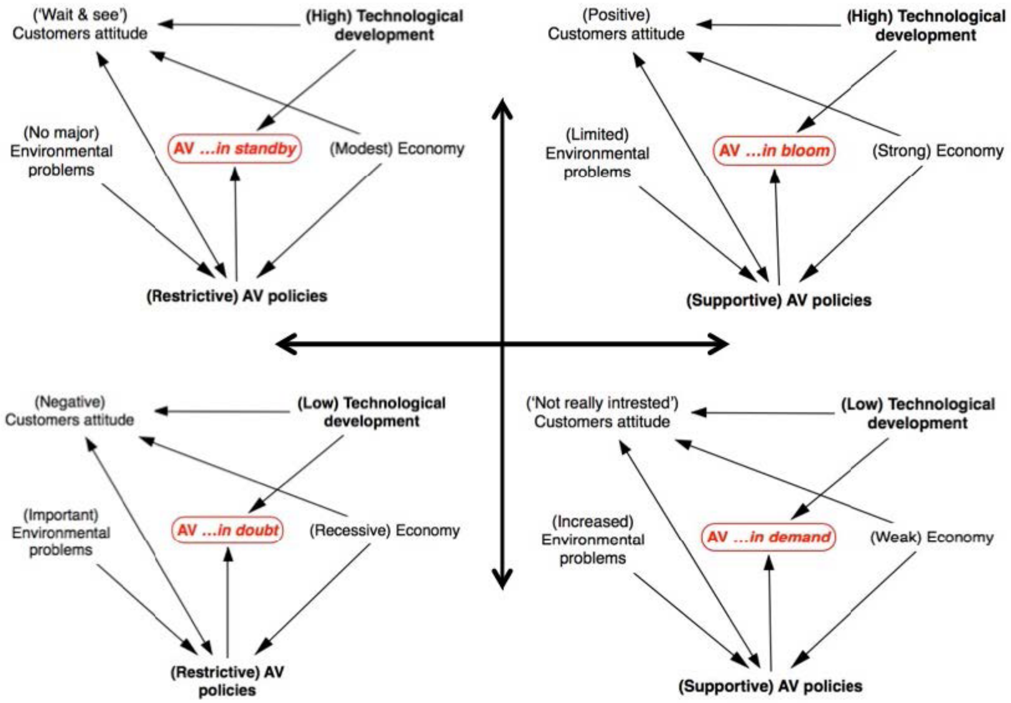
First, key factors and driving forces of the system are identified, and then their level of impact and uncertainty are assessed. Study (4) does this based on interviews with five experts and creates four extreme scenarios using variables with the highest impact and highest uncertainty according to experts' ranking, as shown in Figure 3.1. Study (5) identifies the dependencies and inter-relationships within the driving forces using a causal loop diagram, as shown in Figure 3.2. Clusters of inter-related factors with high uncertainty and high impact are identified to define four scenarios from this diagram. In the final step, Study (4) estimates of penetration rates and potential implications of automated vehicles in each scenario, to assess the likelihood and overall impact of each scenario. Study (5) on the other hand speculates on future scenarios through user narratives, visioning and imagery.

Table 3.4: Studies reviewed and method of scenario construction

ID	Study	Geographic Location	Method
1	(Townsend, 2014)	Atlanta, Los Angeles, New Jersey, Boston (2028-2032)	Alternative futures method
2	(Gruel and Stanford, 2016)	No specific geographic location	System Dynamics approach
3	(Heinrichs, 2016)	No specific geographic location	Systematic literature review
4	(Milakis et al., 2017b)	The Netherlands (2030-2050)	Modified Shell approach
5	(Meyboom, 2018)	United States (2040)	Modified Shell approach

Figure 3.1 Scenario matrix for Study (4)

All interactions between high impact high uncertainty drivers Source: (Milakis et al., 2017b) Figure 13, p. 39



System dynamics approach

Study (2) uses a systems dynamics approach to develop scenarios. It follows a mapping process, identifying key variables and causal relationships among them, through causal loop diagrams, similar to Study (5). The system dynamics model is primarily based on qualitative data collected by the authors through semi-structured interviews and workshops with 30 experts in transportation-planning, the automotive industry, the sharing economy, urban planning, and government policy.

Alternative Futures approach and Systematic Literature Review

Study (1) uses the 'Alternative Futures' approach, developed around the same time as the Shell approach, at the University of Hawaii. In the 'Alternative Futures' approach, stories about the future are grouped together into one of four archetypes – Growth, collapse, constraint and transformation – to develop a text-based narrative for each archetype. Study (3) uses a systematic analysis of a selection of core documents and scenarios with a traceable set of objectives, driving forces and interdependencies, dealing with mobility and its interrelationship with settlement structure. Similar documents are grouped under three types, which are used to define a scenario.

3.2.2 Scenario description

Townsend scenarios

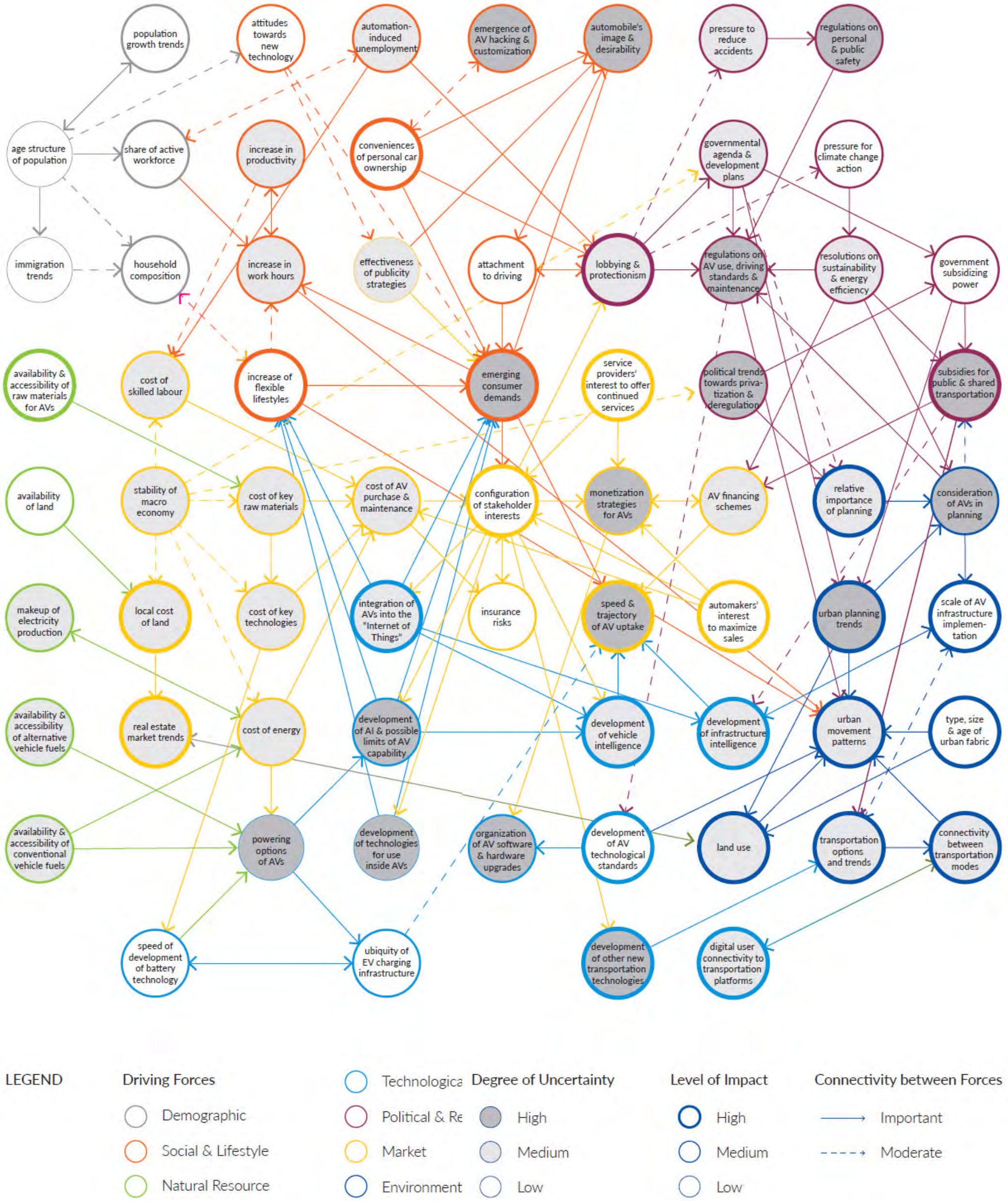
Study (1) proposes four different scenarios, each emerging from different driving forces. In, 'Growth', structural imbalances in the transportation system are addressed through innovation and systemic reforms, which is a fair reflection of present trends extended into the future. 'Collapse' is driven by some critical system failures, where existing imbalances in the transportation system are exacerbated, creating a destabilizing crisis. 'Constraint' scenario is a result of the inability of existing planning and governance structures to deliver transportation infrastructure and services, creating the conditions for a new consensus about the need for collective planning and action. Finally, 'Transformation' emerges organically from a wave of market-driven innovation in both technology and social organization, with the government providing frameworks and platforms for bottom-up change.

Gruel and Stanford Scenarios

Scenarios in Study (2) are driven by two drivers: How will travel behaviour change in response to automation; and how will behaviour regarding ownership change? Based on these drivers, three scenarios were developed. In the first scenario, 'Technology changes, but we don't', AVs are used in the same way as cars are used today and vehicles are privately owned. The second scenario, 'New Technology Drives New Behaviour', assumes significant changes in behaviour related to travel and use of vehicles, but it assumes no change in ownership choices. Finally, 'New Technology Drives New Ownership Models' builds on the behavioural changes of the second scenario but also assumes a complete change in ownership model towards shared AVs.

Figure 3.2 Causal Loop Diagram from Study (5)

Causal loop diagram of driving forces linked together Source: (Meyboom, 2018) Figure 3.1, p. 46



Heinrich scenarios

Study (3) proposes three scenarios, as well. In 'Regenerative/Intelligent City', technological development is coupled with responsible use of resources and supportive legislation to create a flexible, multimodal and networked public transport system. The 'Hypermobile City' emerges from high acceptance of information and communications technology, creating a highly networked automated mass taxi system. Finally, 'Endless City' is a result of limited state power to steer development. The resulting city is predominantly car-dominated with a low level of public transport and a high proportion of informal paratransit use.

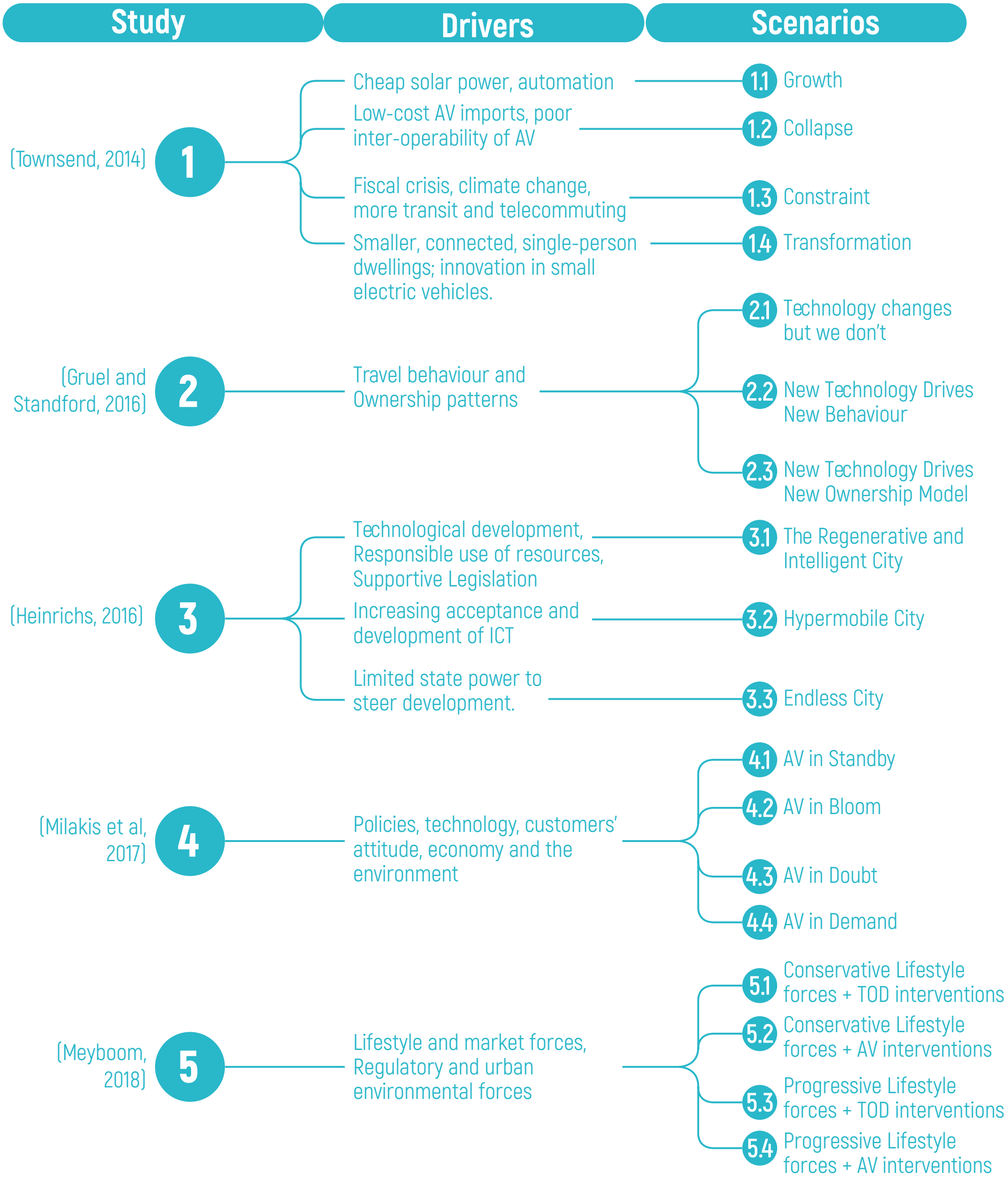
Milakis et al. scenarios

Study (4) develops four extreme scenarios, along two axes – the level of technological development (high or low) and AV policies (restrictive or supportive), as shown in Figure 3.1. When technological development is high, and AV policies are restrictive, we get 'AV in Standby' scenario. In this scenario, customer attitudes are sceptical, economic growth is modest, and there are no strong environmental concerns. With high technological growth and supportive policies, we get 'AV in Bloom' scenario with high economic growth, positive customers' attitudes, and limited environmental problems. Supportive policies with low technological development give us 'AV in Demand' scenario, where the city is plagued by an economic slowdown and environmental problems. Finally, low technological development and restrictive policies lead to 'AV in Doubt' scenario with a weak economy, negative customer attitudes and a prolonged transition to a low carbon economy.

Meyboom scenarios

Study (5) considers two driving forces - lifestyle and market forces which can be either conservative or progressive; and regulatory and urban environmental forces which can support either transit-oriented investment or AV investment, leading to four scenarios. When lifestyle forces are conservative, and transit-oriented development is supportive, the uptake of AV technology is slow, and AV integration in public transit systems takes a relatively long time. Conservative lifestyle forces coupled with investments that support AVs, accelerates the uptake of AVs but commuter habits remain unchanged. Car sharing services take the market share of taxis, with small relative growth. Progressive Lifestyle forces with interventions that support AVs not only lead to quicker technology uptake but also the appearance of a diversity of vehicle types and ownership models in the market. With transit-oriented development, AV sharing services become highly attractive, supported by a robust public transit system. A summary description of all scenarios in the five studies is given in Figure 3.3.

Figure 3.3 Description of all scenarios and driving forces.



3.2.3 Scenario findings

Impact on traffic mobility and value of time

With regards to impacts on traffic flow, Study (2) expects an increase in traffic congestion in both scenarios where only technology and behaviour changes. The impact of changes in ownership model on traffic flow remains uncertain. According to Study (1), widespread gridlock is expected in 'Collapse' scenario. Concerning the value of time, Study (4) expects a decrease from 2% in 'AV in Doubt' scenario to 31% in 'AV in Bloom' scenario.

Space and space use impacts

Under different driving forces, space consumption may increase or decrease. Study (4) expects the effects on road capacity to differ by road type. Road capacity could increase by 6% for urban roads and 25% for highways in 'AV in Bloom' scenario. However, in 'AV in Standby' scenario, road capacity could decrease by as much as 3% for highways. Study (5) expects a reduction in demand for road space in scenarios 5.1 and 5.3, both with TOD interventions. With AV interventions, either no change (conservative lifestyle forces) or an increase in demand for road space in scenarios 5.2 and 5.4 is expected. A reduction of parking space requirement is expected in 'Regenerative/Intelligent City' scenario in Study (3).

Urban sprawl

There are two different effects observed for the urban footprint – further densification or sprawling. In Study (2), higher space consumption and sprawling are expected when behaviour changes, as people travel longer distances than before. 'Hypermobile City' in Study (3) expects an increase in density in the city centres along with the growth of low-density suburbs, while in 'Endless City', a general decline in density and large scale suburban growth is expected. In Study (1), a continuation of sprawling and expansion of 'edge cities' is seen in 'Growth' scenario, a consolidation of suburbs around existing centres is seen in 'Constraint' scenario, and densification around existing transit hubs is seen in 'Transformation' scenario.

Energy Consumption

Similarly, a reduction in energy consumption is expected, but this effect may be cancelled out by other externalities. For example, in Study (2) overall VKT is expected to increases when behaviour changes as well as when ownership patterns change. In Study (4), AVs could account for 71% of the VKT in the 'AV in Bloom' scenario and only 10% in 'AV in Standby'. In Study (5) a slight (scenario 5.1), moderate (scenario 5.2) or large (scenario 5.4) increase in VKT is observed, unless progressive lifestyle forces are combined with TOD interventions (scenario 5.3). In Study (3), 'Regenerative/Intelligent City' shows a reduction in emissions due to greater use of environmentally friendly fuels and sustainable consumption patterns. However, in 'Intelligent City', the high demand for resources may put pressure on the environment.

Impact on transit and active mobility

Impacts on transit ridership and active mobility vary greatly depending on ownership pattern, policy, investment and behavioural changes. In Study (1), if travel behaviour changes as a result of new technology, without a change in ownership pattern, transit ridership decreases. On the other hand, with vehicle sharing, public transit may become more attractive. In study (5), investment in TOD or AV is a driving force of scenario construction. Thus TOD driven scenarios are expected to see a rise in transit ridership and active mobility. In Study (1) there are two extremes – either a complete decline of transit in the 'Growth' scenario or the rise of new forms of DIY transit in 'Collapse' scenario along with a decline in walkability. In Study (3), public transit is the backbone of urban mobility in the 'Regenerative/Intelligent City'. New intermodal mobility hubs are formed as active urban centres. In the 'Hypermobile City', this transit system is replaced by a taxi system. The 'Endless City' is dominated by cars and supplemented by informal paratransit services.

Economic Impacts

Only Study (1) and (2) explicitly address the economic impacts of the technological shift. In scenario 2.1, transport costs are reduced, but when both behaviour and ownership patterns change in scenario 2.3, travel costs increase in low-density sprawls, compared to high-density compact developments. In Study (1), the 'Growth' scenario could be financed through public-private partnerships, 'Collapse' scenario through consumer markets, 'Constraint' scenario through dynamic demand-based transit-pricing and 'Transformation' through tax increment financing of up-zoned development.

3.2.4 Summary of impacts

The following table provides a summary of the impacts of the technological shift in each scenario, within the five themes of interest.

Table 3.5 Summary of impacts in all scenarios

ID	Traffic Flow & Value of Time	Space Use and Consumption	Energy Consumption	Transit & Active Mobility	Economic Affordability
(1) (Townsend, 2014)					
1.1		Renewed exurban sprawl, consolidation and expansion of "edge cities"		Abandonment of transit	Financed by Public-private partnerships
1.2	Widespread gridlock			Decline in walkability and walking, rise of DIY transit networks	Financed by consumer markets
1.3		Consolidation of suburbs around existing centres		Deployment of regional automated bus rapid transit,	Dynamic demand-based transit pricing
1.4	Rapid innovation in logistics and delivery services	Extensive up-zoning of bikeable sheds around existing transit			Tax-increment financing of up-zoned development for infra. improvements
(2) (Gruel and Stanford 2016)					
2.1	More time utilisation in vehicle. Increased traffic volume.		Less energy consumption		Cheaper to travel
2.2	Higher traffic volumes, more congestion.	People are willing to travel longer distances leading to sprawls.	Higher VKT levels	Decrease in transit ridership.	
2.3	Uncertain impacts	Uncertain impact – could increase or decrease sprawl.	Higher VKT levels	If vehicle sharing reverses sprawl to some degree, then public transit may become attractive	Per km travel costs in small, dense areas will be lower than in sprawled-out areas.

ID	Traffic Flow & Value of Time	Space Use and Consumption	Energy Consumption	Transit & Active Mobility	Economic Affordability
(3) (Heinrichs 2016)					
3.1		Reduction in land consumption for urban parking spaces due to new parking systems	Use of environmentally friendly fuels and technologies. Transformation in behaviour of populations – sustainable consumption patterns.	Formation of intermodal mobility hubs. Public transportation's role as the backbone of urban mobility is further expanded.	
3.2		City centres of high density. Growth of low-density suburbs	Very high demand on resources and corresponding environmental consequences	Mass taxi systems will to a great extent replace standard public transportation	
3.3		Suburban growth – General decline of settlement densities	Limited change in consumption patterns and sustainable technology innovation	Car dominated city with informal paratransit services	
(4) (Milakis et al. 2017)					
4.1	Estimation of decrease in value of time of AV users = 21%	% capacity changes in urban roads = 2% and motorways = 7%	% of VKT by AVs in total VKT, in 2050 = 33%		
4.2	Estimation of decrease in value of time of AV users = 31%	% capacity changes in urban roads = 6% and motorways = 25%	% of VKT by AVs in total VKT, in 2050 = 71%		
4.3	Estimation of decrease in value of time of AV users = 16%	% capacity changes in urban roads = 2% and motorways = 5%	% of VKT by AVs in total VKT, in 2050 = 23%		
4.4	Estimation of decrease in value of time of AV users = 2%	% capacity changes in urban roads = -1% and motorways = -3%	% of VKT by AVs in total VKT, in 2050 = 10%		

ID	Traffic Flow & Value of Time	Space Use and Consumption	Energy Consumption	Transit & Active Mobility	Economic Affordability
(5) (Meyboom 2018)					
5.1		Reduced demand for road space	Slight increase in VKT	Increase in public transit mode share	
5.2		No change in demand for road space	Increase in VKT	Decrease in active mobility and public transit mode shares	Increased taxes on driving
5.3		Reduced demand for road space. Great reduction of surface parking.	Slight decrease in VKT	Increase in active mobility and public transit mode shares	Increased taxes on driving
5.4		Increased demand for road space	Large increase in VKT	Large decrease in active mobility and public transit mode shares	

3.3 In summary

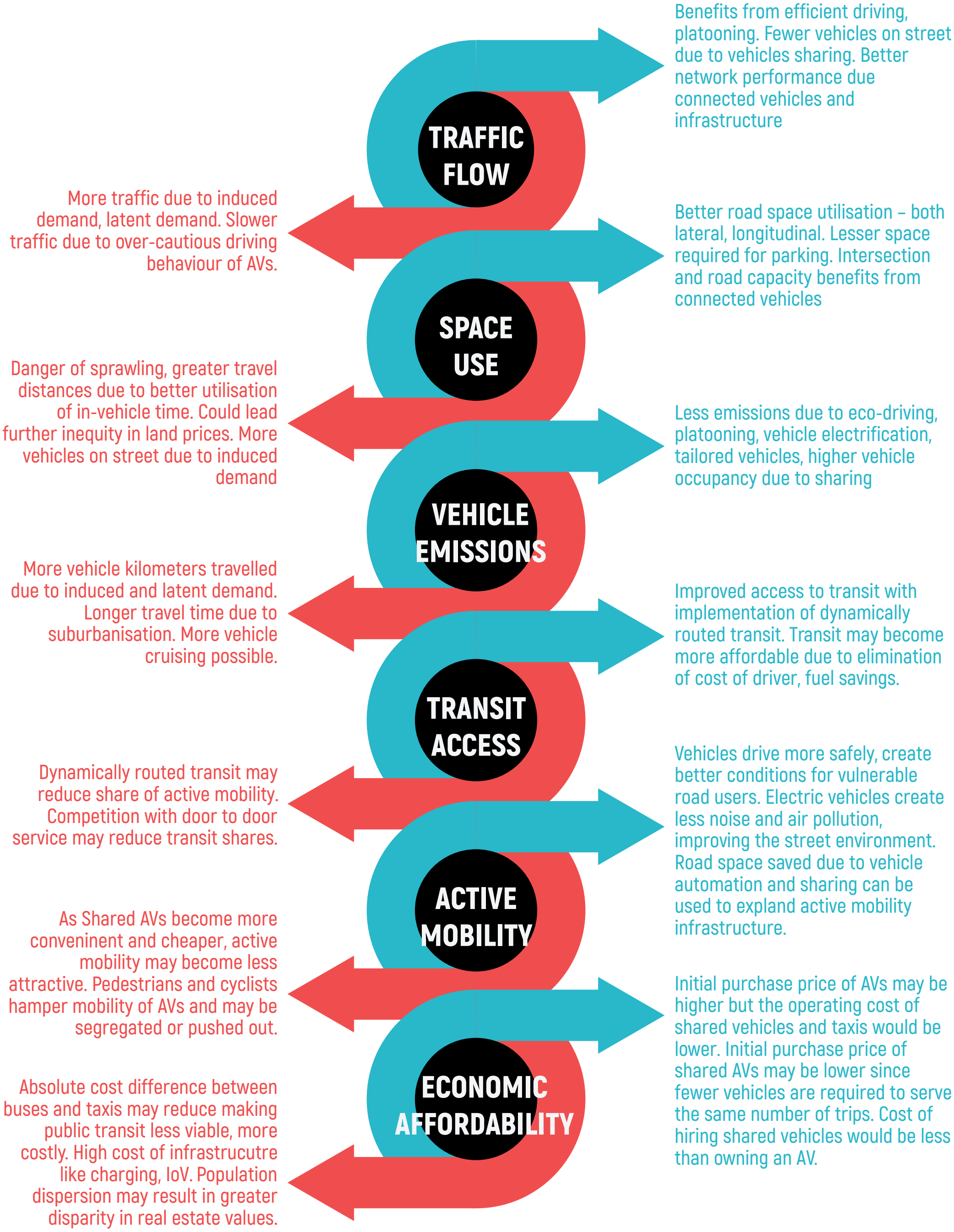
Long term impacts are uncertain

This chapter set out to understand how the technological shift in transportation might impact cities. The literature reviewed here showed that the impacts of the technological shift remain highly uncertain in the long term. The impacts of the technological shift are interconnected and propagate through a 'ripple effect' (Milakis et al., 2017a) that is observed differently over the short and long terms. If the goal of new mobility systems is to improve traffic flow, better utilise space, consume less energy, encourage transit and active mobility and be affordable, it is unclear to what extent the technological shift may contribute to (or be detrimental to) these goals, as shown in Figure 3.4.

Benefits of the technological shift in all themes

The technological shift has the potential to disrupt current automobile-dependent patterns of development. Automated vehicles drive more efficiently, have quicker reaction time and need shorter headways. Connected vehicles allow for better vehicle routing and avoidance of congestion. Vehicle sharing leads to a decrease in vehicle ownership rates. Tailored vehicles can rid themselves of additional safety gear like airbags, and be lighter and right-sized, leading to better fuel efficiency. A combination of these factors can lead to benefits such as better traffic mobility and road capacity gains (both lateral and longitudinal), fuel savings due to 'eco-driving', intersections and parking space savings, fewer vehicles to provide the same level of service, less congestion and safer, more pedestrian-friendly streets.

Figure 3.4 Summary of Impacts of Technological Shift in Transportation on Cities



Benefits from efficient driving, platooning. Fewer vehicles on street due to vehicles sharing. Better network performance due connected vehicles and infrastructure

More traffic due to induced demand, latent demand. Slower traffic due to over-cautious driving behaviour of AVs.

Better road space utilisation – both lateral, longitudinal. Lesser space required for parking. Intersection and road capacity benefits from connected vehicles

Danger of sprawling, greater travel distances due to better utilisation of in-vehicle time. Could lead further inequity in land prices. More vehicles on street due to induced demand

Less emissions due to eco-driving, platooning, vehicle electrification, tailored vehicles, higher vehicle occupancy due to sharing

More vehicle kilometers travelled due to induced and latent demand. Longer travel time due to suburbanisation. More vehicle cruising possible.

Improved access to transit with implementation of dynamically routed transit. Transit may become more affordable due to elimination of cost of driver, fuel savings.

Dynamically routed transit may reduce share of active mobility. Competition with door to door service may reduce transit shares.

Vehicles drive more safely, create better conditions for vulnerable road users. Electric vehicles create less noise and air pollution, improving the street environment. Road space saved due to vehicle automation and sharing can be used to expland active mobility infrastructure.

As Shared AVs become more conveninent and cheaper, active mobility may become less attractive. Pedestrians and cyclists hamper mobility of AVs and may be segregated or pushed out.

Initial purchase price of AVs may be higher but the operating cost of shared vehicles and taxis would be lower. Initial purchase price of shared AVs may be lower since fewer vehicles are required to serve the same number of trips. Cost of hiring shared vehicles would be less than owning an AV.

Absolute cost difference between buses and taxis may reduce making public transit less viable, more costly. High cost of infrastrucutre like charging, IoV. Population dispersion may result in greater disparity in real estate values.

Threats of the technological shift in all themes

On the other hand, the technological shift can be equally detrimental to these mobility goals, furthering the car-oriented development patterns of today. Instead of practising eco-driving, AVs may drive at higher speeds than today, leading to time gains, but more fuel consumption. Vehicle sharing may lead to fewer vehicles on streets, but detours and empty travel may increase congestion and fuel consumption. Change in value of in-vehicle travel time may lead to induced demand and changes in home and job location choices leading to urban sprawl. Latent demand from those sections of the population that are currently unable to drive will also add to the induced demand.

Variations in benefits and threats by user or goal

In the process of maximising the benefits for one user group or mobility goal, other user groups or mobility goals may suffer. For example, the real benefits of platooning cannot be realised unless stopping and braking instances are minimised, or the distance between intersections is maximised, which can, in turn, lead to longer walking distances for pedestrians. Slot-based intersections are also not compatible with pedestrians and cyclists. These observations point towards more segregation of infrastructure by mode, reminiscent of modernist visions for car-based cities. It is imperative to make our priorities explicit and collectively set benchmarks for minimum levels of service with appropriate indicators to measure them.

Holistic scenario studies and driving forces of the shift

It is difficult to quantitatively predict the long-term consequences of new technological deployments, which is why we often pursue more predictable short-term benefits (Cannon, 1973). However, short term benefits for an isolated group or goal may result in unintended consequences in the long term. The studies regarding isolated impacts of the technological shift reviewed here take a rather technocratic standpoint, and their conclusions are likely to differ from the aggregate effect when these technologies are deployed within an existing context (Laurie Laybourn-Langton, 2017). The holistic scenarios studies reviewed here, take these aggregate effects into account to a certain extent.

Four driving forces will determine the magnitude and impacts of the technological shift, as identified from the studies reviewed here.

1. Pace of technological development

The pace at which each of the technologies discussed in Section 2.2 develop, from experimental tests to market-ready products, is a crucial driving factor. Early forecasts of diffusion rates for innovations tend to be far too optimistic due to ‘technological hype’ (Amara, 1990), but almost always end up slower than expected. Chan (2017) believes that while technologies on all fronts have leapt forward tremendously, extensive development work is required to turn them into products. Meyboom’s study on the impact of AVs reviewed here found capabilities of AV, speed and trajectory of AV uptake, powering options for electric vehicles and development of AI and other new competing technologies as the most uncertain driving forces of the technological shift (Meyboom, 2018). Milakis et al. (2017b) also identify technology as the most important driving force.

2. Public acceptance and social factors

In addition to technological development, the level of uptake will determine its rate of diffusion in society. In the Milakis et al. (2017b) study, this was found to be the driving force with the highest level of uncertainty. Are customers willing to pay for additional features of automation? How will people perceive a vehicle driven by a machine? Kyriakidis et al. (2017) stress the importance of more research on public acceptance and trust in automation and the interaction with AVs. For example, Lavieri et al. (2016) used survey data collected in Washington, United States, and found that younger, urban residents with a high level of education are more likely to be early adopters of AVs. Citymobil2 project, an AV pilot in The Netherlands, offered a unique opportunity to investigate attitude of users towards shared automated vehicles. The results of their survey show that automation is not necessarily perceived as valuable if the travel time and fare are the same as those of a conventional bus (Alessandrini et al., 2014). Thus public acceptance also depends on operational policy and regulations.

3. Operational policy and regulations

Proactive actions on policy and regulation may ensure rapid uptake of technology and reactive or inert actions may delay the process. Regulating policies revolve around issues such as testing and deployment, cybersecurity and privacy, liabilities and insurance, ethics, and most importantly, pricing and ownership. How self-driving cars will change cities depends on who owns them. More private ownership may lead to a dramatic increase in VKT, corporate ownership may lead to inequity of access, and public ownership requires a large private investment or public subsidies in order to be successful (Grush and Niles, 2016). The pressure for climate change action and resolution on sustainability and energy efficiency may lead to environmental regulations that would, in turn, determine the pace of technological development and uptake of technologies like electric vehicles and vehicle sharing. Although Milakis et al. (2017b) identified the environment as the least impactful driver in the study reviewed here, they also identified it as the most certain.

4. Urban planning and design

Urban design and planning strategies can be employed to modify travel behaviour and is an essential driver in the context of this research. Carefully thought out pro-active urban planning strategies can be a useful tool to maximise the benefits of new transport technologies and minimise their potential dangers. Meyboom (2018) identifies several such planning strategies, such as land use planning, urban network structure, type, size and age of existing urban fabric and scale of AV infrastructure implementation. Given the two-way relationship between urban form and transport flows, an urban design response to the technological shift in transportation is necessary. This two-way relationship and some urban design responses to the technological shift in transportation are elaborated in the next chapters.

4 Responses to the Technological Shift in Urban Design Practice

So far, we have looked at how the technological shift in transportation will make new demands of existing transport infrastructure and passively impact the city, its physical form and transport flows. One may argue that technologies such as vehicle automation are inconsequential from an urban design standpoint. Since even if a vehicle is automated, it should act no different with respect to urban infrastructure, using the same roads and parking. Such thinking discourages urban designers and planners from participating in a conversation that is currently dominated by techno-centric points of view. The focus remains on questions regarding how existing cars can be given a technical fix to decrease fuel consumption or how existing public transport can be improved a bit.

Instead of emphasising the benefits of technology and its potential to transform the city, the focus must shift to what type of future city we want and how may the technological shift enable (or hinder) it. Contemporary urban design practice has been speculating regarding the new requirements posed by the technological shift and responding through a range of design proposals and strategies. In this chapter, we will briefly discuss some of these design strategies, clustered within five aspects of the urban form: street design, parking design, pick-up/drop-off interface design, design of intersections and network structure. A diagrammatic catalogue with all the design strategies discussed here is shown in Figure 5.1.

Figure 4.1 A catalogue of design strategies in response to the technological shift in Transportation

Street Design

Reclaiming street space

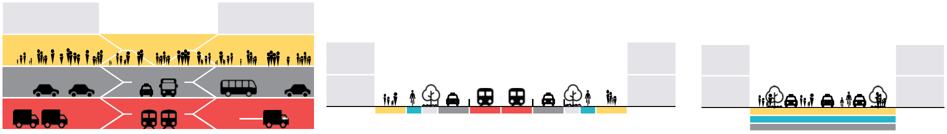
Present situation

Reducing lane width

Reducing number of lanes

- 🟨 Pedestrian zone
- 🟦 Cyclist zone
- ⬜ Traffic zone
- 🟥 Train zone

Segregating street space

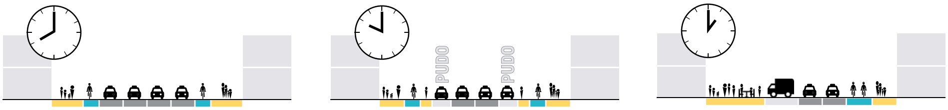


Grade Separation

At-grade segregation

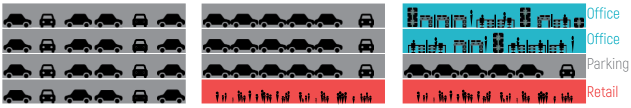
Shared street

Responsive street

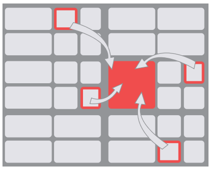


Parking Design

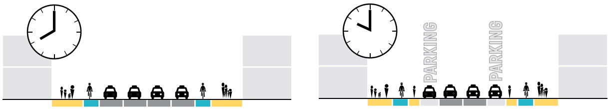
Reclaiming parking space



Shared parking depot



Redefining on-street parking



PUDO Design

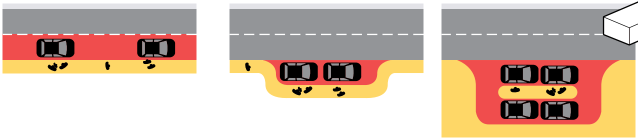
On-street PUDO

🟨 Pedestrian 🟥 PUDO ⬜ Traffic

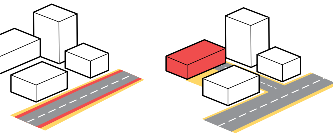
Stop and go lanes

Bay-based PUDO

Double Bay PUDO

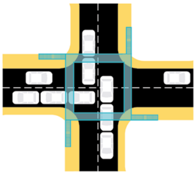


Off-street PUDO



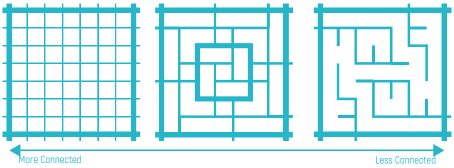
Intersection Design

AV Priority



Pedestrian Priority

Network structure



4.1 Street design

Changes in street design are one of the most common responses to the technological shift in urban design. When only fully automated vehicles operate on urban streets, street design norms and standards can be redefined to reclaim street space for other uses. The second area of intervention is the segregation between automated and non-automated actors of the street, for which various contradictory solutions can be found. The third type of intervention is 'responsive street' design that maximises the capabilities of extensive V2I connectivity and sensors in the environment.

4.1.1 Reclaiming street space

Reducing street widths

A direct response to vehicle automation is a reduction in minimum lane width standards of traffic lanes since AVs can drive much more precisely, as discussed in section 3.1.1. Lane widths could be reduced to as low as 2.5 meters for streets with no buses or trucks. Based on this, enough space can be reclaimed from a four-lane street to add a two-way bicycle lane, or an additional on-street parking lane, as shown in Figure 4.2. City of San Francisco's entry to the Smart City Challenge (2016) used a similar strategy, gradually reducing the area dedicated to traffic and increasing the area for pedestrian-oriented activities over time as technology develops, as shown in Figure 4.3.

Reducing the number of lanes

A reduction in lane width does not imply a reduction in the volume of traffic flow. As we saw in section 3.1.2, the technological shift will lead to lateral as well as longitudinal gains in street capacity. Improvements in traffic flow may lead to induced demand, and almost triple the total number of trips (refer to (Ambühl et al., 2016)). In order to curb this induced demand, a reduction in the overall number of lanes is encouraged. SFMTA's entry to Smart City Challenge also proposes a reduction in lanes when all vehicles are shared and connected in addition to being automated, as shown in the right image block in Figure 4.3.

Issues with reclaiming street space

Reclaiming street space may not be a practical solution in all contexts. Uniform reductions in lane widths are not feasible where larger vehicles for transit, deliveries and emergencies, need to operate. Cyclist and pedestrian infrastructure cannot be designed in a piecemeal manner by adding new infrastructure selectively on reclaimed streets space. For the same reason, entire lanes cannot be removed selectively from streets where lane capacities are underutilised. It is difficult to predict how much street space can be reclaimed without causing bottlenecks further downstream due to emergent network effects. Where traffic flow is not compromised by reclaiming street space, for example at large cul-de-sacs (see Figure 4.4), it is not certain that the new land use in the reclaimed space can be supported by the existing land use mix and density around it.

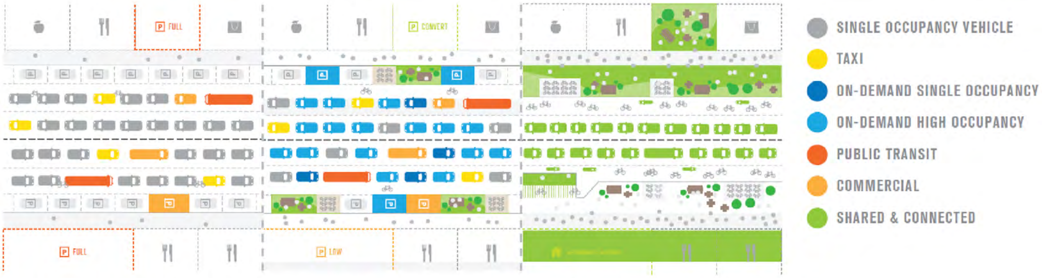
Figure 4.2 Three ways to reclaim street space

Present situation

Reducing lane width

Reducing number of lanes

Figure 4.3 San Francisco's entry to Smart City Challenge
Source: SFMTA



Personal Ownership Model

Shared On-demand

Shared Electric Connected AVs

Figure 4.4 Reclaiming cul-de-sac as a public space
Source: (Baumgardner, 2016)

4.1.2 Segregating street space

To segregate or not?

One of the more contentious issues regarding street design in the context of the technological shift is whether to segregate automated vehicles from the rest of the traffic and to what extent. Recall that when the private automobile became ubiquitous, physically segregation from all other modes became a popular design strategy, as discussed in section 1.1. Should street space be similarly compartmentalised for AVs and shared vehicles? If yes, how should this segregation be designed?

Two views on segregating by mode

There are two views on the question of segregation by mode. According to one, automated vehicles drive much more cautiously than human-driven vehicles, making them much safer in shared street spaces. In this view, minimal to no segregation between modes is recommended. In opposition to this, some commentators believe that AVs cannot be expected to operate efficiently in a shared environment since humans are unpredictable, and technology cannot possibly anticipate all behaviours. People may also take advantage of the cautious driving behaviour of an AV to jaywalk more often, hindering traffic flow. In this view, strong segregation is advocated. We consider three types of separation here, as shown in Figure 4.5, a separation through grade, an at grade separation with a buffer, and no separation at all through shared street design.

Compartmentalisation through grade separation

AVs can be segregated from pedestrians and other modes through grade separation, similar to many elevated highways today. Grade separation on streets has always been a contentious subject, and often unsuccessful when implemented. It is criticised for creating lifeless pedestrian environments and physical barriers between neighbourhoods. These issues may be overcome through careful design that integrates the overall land use plan and active mobility network. Both in NODE Architecture's proposal for Shenzhen 2030 as well as Singapore's vision for AV enabled future, shown in Figure 4.6, have high-speed transit, logistics and services in underground tunnels, freeing up the ground surface for active modes and activity generating uses. In EDG's Loop NYC proposal shown in the bottom of the same figure, the pastoral parks filled with bicycles, trees and rolling hills over a tunnelled Broadway street is not necessarily an improvement over the active retail filled, albeit traffic-clogged, Broadway of today.

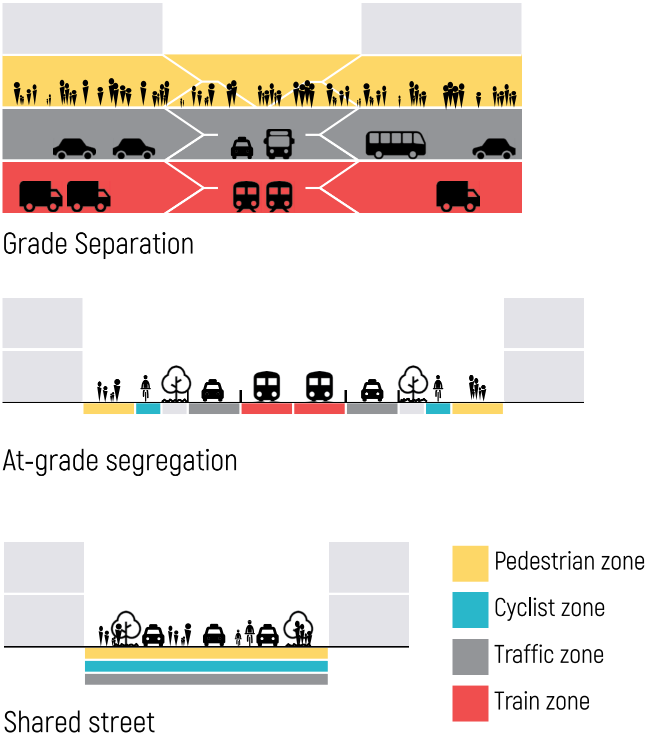
At grade separation

Another way to segregate traffic is through at-grade physical buffers such as fences or greenery. WSP Parsons Brinckerhoff use the buffer between a motorway and cycle lanes as a solar farm, as shown in Figure 4.7. At-grade separation allows better physical and visual connections, but it is not suitable for all locations and street types. While the street in Figure 4.7 is well suited to strong at-grade separation, streets that need frequent crossing opportunities for pedestrians, such as a retail lined street, do not function well with at-grade separation.

Shared streets

In the ideal case where vehicle automation technology is advanced enough to function efficiently in highly mixed environments, shared streets are the preferred design strategy. Shared streets have no physical or visual markers of segregation between different users of the street. Zones on these streets are completely pervious and visually indistinguishable. One example of such a shared street with AVs can be seen in BIG Architects' proposal Driver(less) is more, submitted to Audi Urban future award in 2010, shown in Figure 4.8. Concerns such as trust in the technology and losses in traffic mobility must also be considered. Are we slowing down the overall network? Is the land use diverse enough within the walkshed of the shared street to maintain its vitality? Care must also be taken to ensure uninterrupted mobility for transit vehicles, emergency vehicles and the elderly and disabled population.

Figure 4.5 Three ways to segregate street space



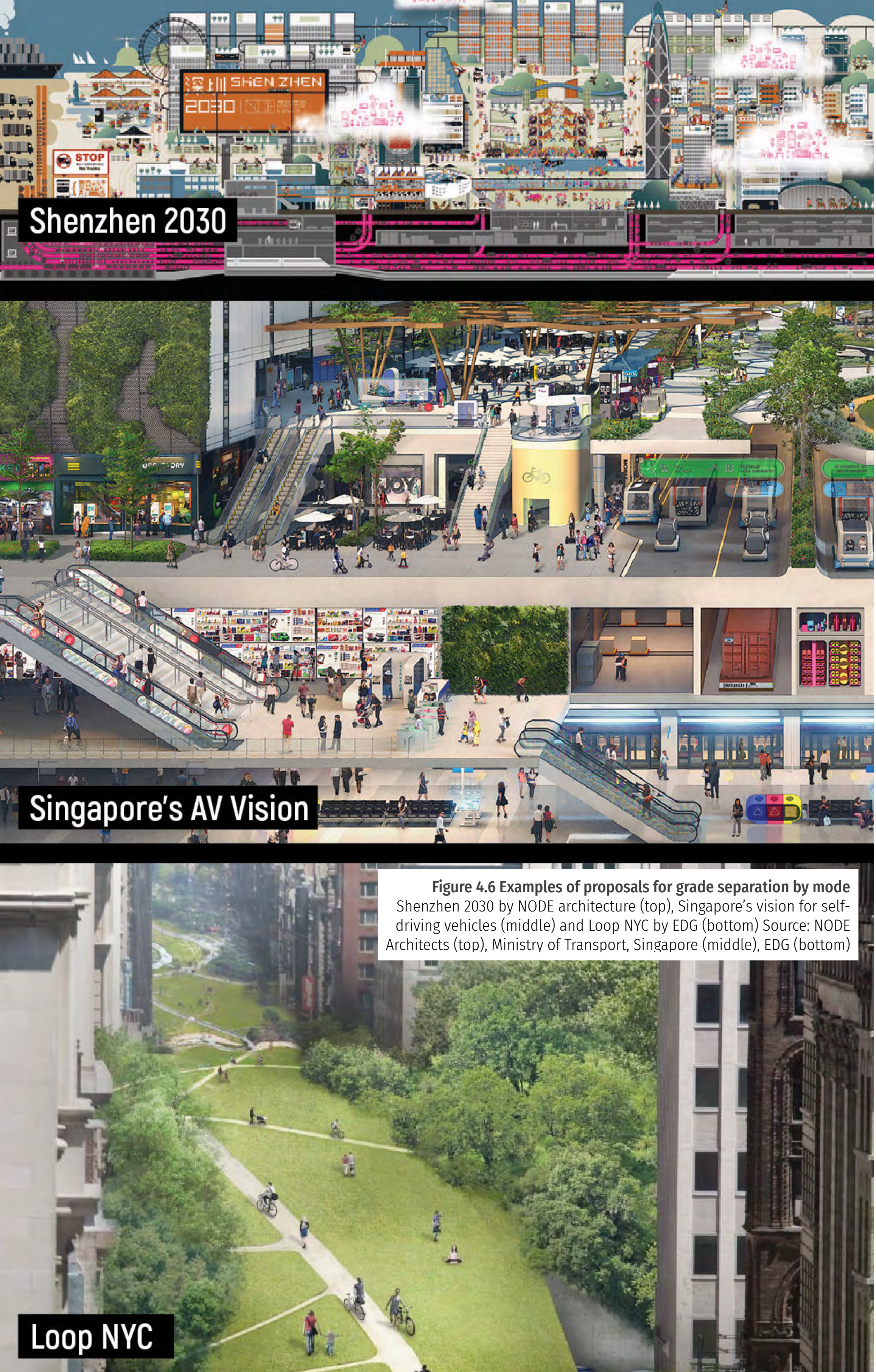


Figure 4.6 Examples of proposals for grade separation by mode
Shenzhen 2030 by NODE architecture (top), Singapore's vision for self-driving vehicles (middle) and Loop NYC by EDG (bottom) Source: NODE Architects (top), Ministry of Transport, Singapore (middle), EDG (bottom)

Figure 4.7 At-grade separation
A physical buffer created by solar panels Source: WSP Parsons Brinckerhoff and Farrells

Figure 4.8 BIG architects' driver(less) is more
Proposal for a shared street by BIG Architects for the Audi Urban Future Award 2010 Source: archdaily.com

4.1.3 Responsive street design

Responsive streets

A common response to the technological shift in transportation, particularly to connected vehicles and infrastructure, is responsive street design. Street zones and their use can change dynamically on a responsive street, based on the demand, time of day or other requirements, as shown in Figure 4.9. Such responsive streets are a radical departure from physical segregation towards virtualisation of street zones. For example, a busy four-lane street during peak hour can change into a one-lane one-way street with parking area for food trucks during lunch hour. According to Levin and Khani (2018), *dynamic transit lanes* can improve transit accessibility at small spatial and temporal intervals, giving access to private vehicles when transit is not present. Hausknecht et al. (2011) also proposed a *dynamic lane reversal system*, in which lane directions change at small temporal intervals (such as 1 min or less).

Flexible streets by sidewalks labs

A prominent example of responsive streets design is Sidewalk Labs' flexible streets in Toronto (see Figure 4.10). Carlo Ratti and his team created a prototype street using a reconfigurable modular paving system that can change the use of a street throughout the day (Rima Sabina Aouf, 2018). The hexagonal panels are removable and easy to rearrange, making all kinds of configurations possible. The pavers are embedded with lights to communicate signals like crossings, bike lanes and pick-up zones, to pedestrians and cyclists, which is a very light form of zonal demarcation. Each paver also has a slot for inserting vertical elements like bollards, which can enable conventional hard segregation between zones.

Other design variations of responsive streets

Other examples of responsive streets include 'Flex-zones' by Riggs et al. (2019), the 'Tripanel' by the 2012 Audi Urban Future Award winner Howeler+Yoon, that rotates between paving, park and solar panels (Figure 4.22); and the 8 sqft plug and play system in 'Public Square' by FX Collaborative, winners of Driverless Future Challenge 2017. All proposals provide complete physical permeability between zones, with some sort of visual marker of street zones, such as lights, paving patterns or textures. There is a wide range of functions accommodated in these responsive streets beyond its traditional traffic function such as parks, bio-swales, pick-up/drop-off lanes, art installations or solar panels.

Issues with responsive streets

The critical issue with responsive street design is the reliability and usability of the technical systems needed to make it work. Are soft signals of demarcation like paving patterns or coloured lights adequate to convey information to all types of users? Qualitative and cognitive studies of user experience are needed to understand the usability of such systems. The mechanism by which uses will be assigned to different zones on the street, over the day, week or year, is also unclear. Today we predict transport flows using static quantities of land use and transport infrastructure provision. As transport infrastructure capacities and public space provision become more dynamic, new types of tools will be needed to predict transport flows and design infrastructure for it.

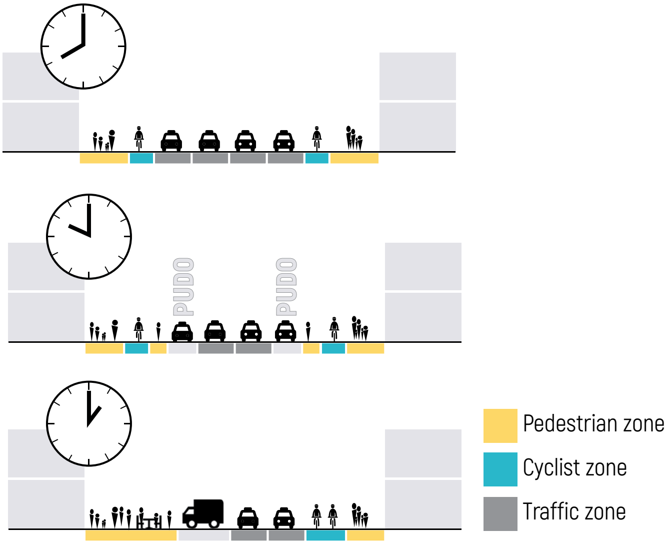


Figure 4.9 Responsive streets

Figure 4.10 Sidewalk Lab's Dynamic Street
Proposed by Carlo Ratti Associates and Sidewalk Labs
Source: Photo by David Pike obtained from (Rima Sabina Aouf, 2018)

4.2 Parking design

A large portion of the space for transportation infrastructure is dedicated to parking, which is also currently massively underutilised. Urban design practice, real estate companies as well as city governments are currently grappling with the question the future of parking in the context of the technological shift in transportation. Three types of interventions can usually be found in this respect: reclaiming parking space, designing shared parking depot and redefining on-street parking.

4.2.1 Reclaiming parking space

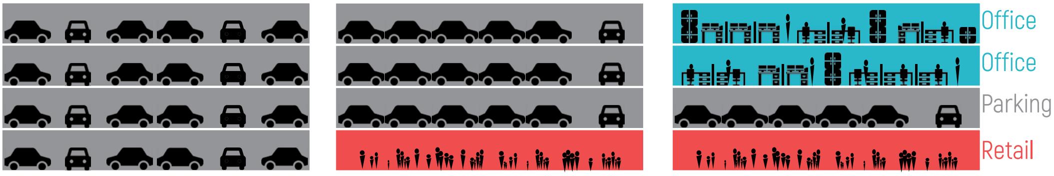
Reclaiming parking space

Automation allows vehicles to park in much tighter spaces, dramatically reducing the space required for parking, allowing us to redefine parking design norms and reclaim a considerable amount of parking space, as shown in Figure 4.11. While existing parking facilities have islands with only two rows of vehicles, future designs tailored for AVs can have multiple rows of vehicles stacked behind each other, as shown in Figure 4.12. Nourinejad et al. (2018) tested various car-park layout designs that minimize relocations while fitting a given number of vehicles in the car park and found that AV car-parks can decrease the need for parking space by an average of 62% and a maximum of 87%.

Further reduction in space requirement due to sharing

Further parking space can be reclaimed when more vehicles are shared, and the overall vehicle stock declines. Parking minimum norms can be revisited in such a scenario, and new parking structures can be designed to adapt to multiple uses in the future. Unused space in a conventional parking garage can transform into a multi-purpose building with pick-up/drop-off activity, electric vehicle charging facility, residential, office or recreational spaces.

Figure 4.11 Progressively reclaiming parking space



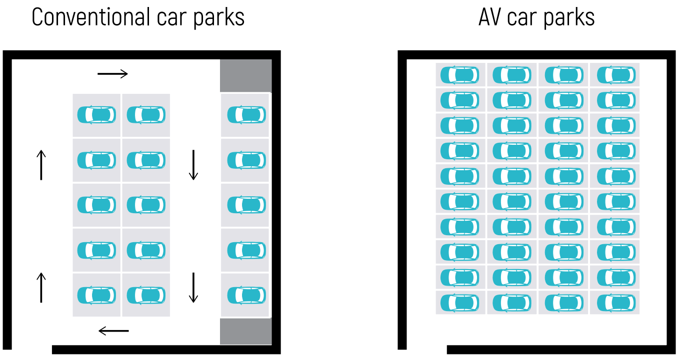


Figure 4.12 Parking design for AV
Stacks of multiple rows on the right, compared to conventional two-row parking on the left
Source: Adapted from (Nourinejad et al., 2018), Fig. 1, p. 111

4.2.2 Shared parking depots

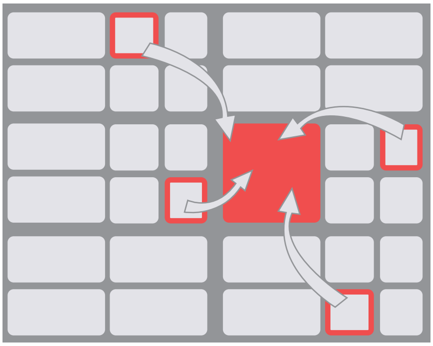
Shared integrated parking depot

Instead of providing multiple dedicated parking structures, all parking provision can be consolidated in one shared integrated parking depot (Figure 4.13). According to Rodrigue et al. (2013), we design two off-street and two on-street parking spaces for every car in a motorised city. With AVs, this duplication will become redundant, since even privately owned AVs may drop the owners to their destinations and drive themselves back home. However, there is a danger that this would generate a large amount of empty VKT, emissions and congestion on the road. To avoid this, we need to move away from private parking garages towards shared parking depots. Such a depot is expected to require less space than the conventional dedicated parking structures, and potentially also reduce empty VKT. When designed together with other facilities such as transit and retail hubs, they could transform into a vibrant environment and even encourage transit and active mobility.

Concerns regarding shared depots

We can foresee some issues with such shared depots. People may not be willing to give up private parking spaces and use a shared parking garage exclusively. The design of such a garage will also need to be optimised carefully to minimise vehicle relocations internally. The fewer the depots, the more vehicles can be consolidated, optimising the use of infrastructure. However, fewer depots also mean longer distance from destinations and increase in empty VKT. This effect will be heightened if the parking depots are located in off-street external sites due to lower real estate values in these areas (Metz, 2018; Noyman et al., 2017).

Figure 4.13 Consolidating parking



4.2.3 Redefining on-street parking

Redefining on-street parking

As overall vehicle stock declines due to the increase in vehicle sharing, it can be argued that the entire parking demand can be met through on-street parking in reclaimed traffic lanes. As the number of shared vehicles increases, demand for private vehicle parking will decrease, as will the number of parked vehicles during peak hour. Lanes can dynamically change from traffic to parking lanes from peak to off-peak hours. Responsive streets discussed in section 4.1.3 could be designed to accommodate such on-street parking, as shown in the SF Smart City Challenge entry in Figure 4.3.

Challenges with on-street parking

On-street parking can also double up as pick-up/drop-off (PUDO) points. Care must be taken to provide enough space for PUDO activity so as not to create spillback effects in the network. In future, a suitable pricing model for curbside use must be adopted, that allows the city to recover the loss of revenue stream from traditional parking. At the same time, curbside use charges should not encourage cruising behaviour by empty vehicles.

4.3 Pick-up/Drop-off (PUDO) design

PUDO design is one of the most significant areas of change in the urban form in response to the technological shift. PUDO activity is conducted today by various methods, from curbside hailing of taxis, to dedicated taxi pick-up/drop off infrastructure. In future, with increased vehicle sharing, PUDO activity will increase considerably, and the existing infrastructure may not be enough to cater to this growing demand. Even privately owned vehicles may need PUDO infrastructure if they are automated. The diversity in vehicle size, from a small two-seater AV to larger 15 seater shuttles, would also need to be accommodated in PUDO zones. PUDO design needs to be reimagined to cater to all these users. There are two types of PUDO spaces that can be considered: on-street PUDO areas and off-street PUDO hubs (Figure 4.15).

Figure 4.14 Dynamic parking lanes

4.3.1 On-street PUDO area

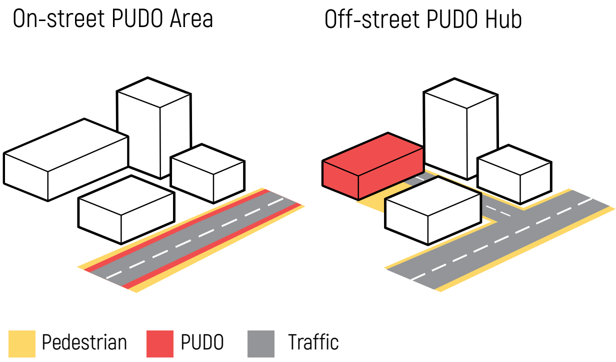
Stop and go lanes

Curbside pick-up and drop-off activity can be organised in two ways – through stop and go lanes or bays (Figure 4.16). The former resembles curbside ride-hailing activity we have today, where vehicles are allowed to stop and go in the sidewalk-side lane. With an increase in street capacity, we may assume that such a stop and go lane can be provided on most streets without seriously disrupting the traffic flow. However, an increase in vehicle sharing will also dramatically increase PUDO activity, which may challenge this assumption. The volume of PUDO activity is dependent upon density and land use in the surrounding urban blocks and level of sharing and occupancy per vehicle. Increase in PUDO activity may block the stop and go lane, or increase waiting times due to congestion or spill-over of waiting vehicles to surrounding links. A second strategy, bay-based curbside PUDO space can be designed in this case.

Bay-based PUDO

A bay-based PUDO space is located outside of the traffic flow, which provides extra space for dwelling vehicles to perform PUDO activity without disrupting the traffic flow. However, there is some time lost by vehicles conducting PUDO activity, in exiting and re-entering the traffic flow. Additionally, even with dedicated bays, traffic lanes may be blocked by waiting vehicles if the size of the bay is too small to accommodate all waiting vehicles. A larger bay, spanning the whole length of the street, or a double bay PUDO area can be designed in such cases, depending on the space available (see Figure 4.16). Care must be taken to design on-street PUDO spaces in such a way that it does not obstruct flow in bicycle lanes. Both on-street stop and go lanes and bays can double up as on-street parking, reducing the spatial imprint of transport infrastructure.

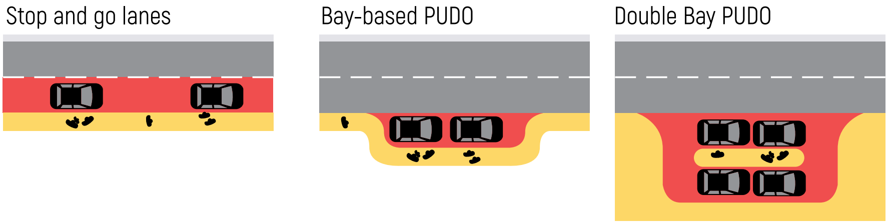
Figure 4.15 Two types of PUDO strategies



On-street PUDO Area

Off-street PUDO Hub

Figure 4.16 Three types of on-street PUDO



Stop and go lanes

Bay-based PUDO

Double Bay PUDO

4.3.2 Off-street PUDO hubs

Off-street PUDO Hubs

Fundamentally, on-street PUDOs offer many conveniences to users, but they always run the risk of creating congestion through spill-over of waiting vehicles. The second method of organising PUDO activity is through off-street PUDO hubs. Instead of providing many PUDO bays, fewer but larger off-street PUDO hubs can be provided in strategic locations. Such hubs keep the waiting vehicles outside of the traffic by consolidating them in one central location. These PUDO hubs can be seamlessly integrated with other transit hubs, such as train stations or bus stops, to encourage greater use of transit. They can also be integrated with shared parking depots, and activity generating facilities such as shopping malls, to create vibrant new spaces of activity and mobility in the city. A visualisation of such an integrated PUDO with parking and activity spaces was proposed by Audi, shown in Figure 4.17.

Issues with off-street PUDO

If located in a mono-functional land use context, these large PUDO hubs would be active for limited hours of the day and could become large dead spaces during off-peak hours. On-street PUDO spaces, on the other hand, are more active. Seamless integration between modes, legibility and ease of access for pedestrians, and land use planning in the vicinity are the main design challenges for PUDO hubs.

4.4 Intersection design

The design of intersection is expected to change in response to the technological shift in transportation. Traffic signals came into prominence with the growing number of automobiles on the streets and the chaos that ensued at unregulated intersections. As vehicles become automated and connected, will traffic signals become obsolete? If so, what would replace it? There are two design responses possible, one which prioritises the AVs and the second which prioritises pedestrians.

4.4.1 AV priority intersections

Increase in intersection capacity and SI

The traffic light is a century-old technology that may become redundant in the context of the technological shift. The best way to maximise the performance of automated vehicles is through non-signalised intersections with grade-separated crossings for pedestrians and cyclists. Slot-based intersections (SI) can be used to manage traffic, similar to the system used in managing aerial traffic. Time slots are assigned to individual vehicles to access the intersection area based on a scheduling algorithm (Tachet et al., 2016). In Section 3.1.1, we discussed that SI could increase intersection capacity by 100%, as compared 40% increase due to connected automated vehicles on a signalised intersection.

Need for physical segregation of pedestrians from traffic

Pedestrians and cyclists cannot navigate such a signal-less intersection and need a stopping phase with traffic lights. The capacity of intersection can be maximised and delays minimised through grade separate pedestrian crossing, to ensure continuous flow for both traffic and pedestrians. Separation of pedestrians from AV traffic is not only preferable at intersections but also along the streets. According to Tachet et al. (2016), the first-come-first-serve approach of SI is not efficient at high vehicle arrival rates.

Problems with physical segregation

Grade-separated crossings eliminate waiting time for pedestrians at intersections but add other impedances. Erath et al. (2016) conducted a stated and revealed preference study in Singapore to understand the pedestrian route choice behaviour and found that pedestrian overpasses were unpopular and avoided by pedestrians. The respondents were willing to make a detour of 120-220 meters, to avoid overpasses with and without an elevator, respectively. Considering that 95% of the trips they observed were less than 500m and the median walking distance was 213m, overpasses can have a significant disutility, forcing pedestrians to drive even for short trips. The same study also found that walking along a busy road is perceived as longer than the actual distance. A physical barrier between the sidewalk and the traffic lanes, such as a green median, could prevent road accidents and provide a buffer from high-speed platoons. However, a buffer may also directly harm the objective of providing a tightly connected pedestrian network.

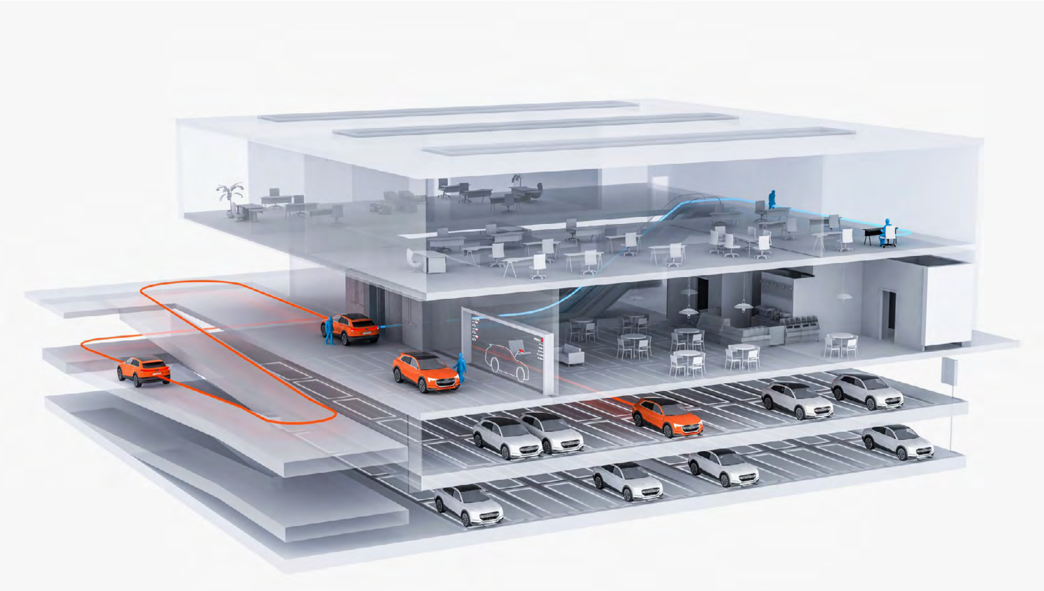
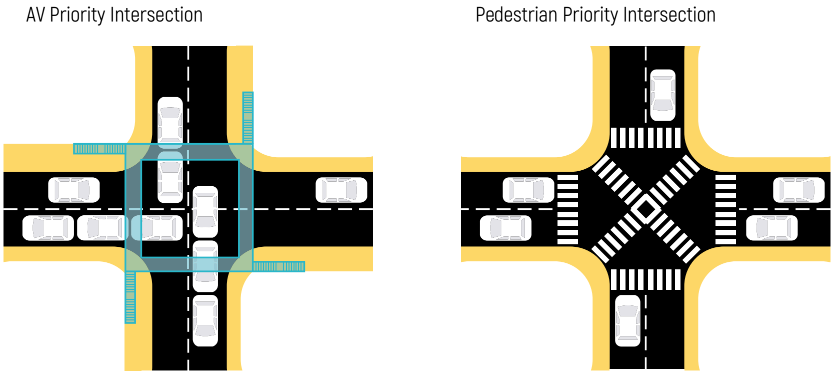


Figure 4.17 Integrated parking and PUDO
Source: Audi



AV Priority Intersection

Pedestrian Priority Intersection

Figure 4.18 Two types of intersection design strategies

4.4.2 Pedestrian priority intersections

Mixed AV and pedestrian priority strategies

A pedestrian priority strategy for intersection design maximises pedestrian accessibility, irrespective of its impact on traffic capacity at an intersection. In this case, only at-grade crossings are provided, which can be designed in different ways, such as offsetting the crossing location, as shown in Figure 4.19, or providing scramble crossings as shown in Figure 4.18.

Offsetting pedestrian crossings

Today most pedestrian crossings exist at controlled intersections for safety reasons. If all vehicles on the road are connected and automated, crosswalks could be placed at any location along the street that is optimal for pedestrians (Gjerdingen, 2016). In a design proposal by SEH Inc., the pedestrian crossings are at-grade but offset by a considerable distance from the intersection, as shown in Figure 4.19 . Offsetting the pedestrian crossing from intersection improves pedestrian accessibility by directly connecting destinations through the shortest routes. However, these crossings create additional points of conflict for vehicular traffic and cyclists.

Scramble crossing

Pedestrian accessibility at intersections can also be improved by providing scramble crossings, a type of traffic signal that temporarily stops vehicular traffic in all directions, thereby allowing pedestrians to cross an intersection in every direction, including diagonally, at the same time. Since all vehicular traffic is stopped rather than allowing partial vehicle movements to coexist with partial pedestrian movements, the pedestrian scramble has sometimes been seen as inefficient by traffic engineers. Under certain circumstances, pedestrian scrambles could reduce safety, as the average waiting times for pedestrians and car drivers are increased, thus creating more likelihood of people disobeying the signals (Bechtel et al., 2003). Both these issues can easily be overcome with connected automated vehicles and an SI with stopping phases.

4.5 Network structure

The street network is arguably the most impactful restructuring element of the urban form. It is difficult to define a particular network 'type', since any urban network is a combination of different patterns, and varies at different scales. Marshall (2004) attempted to create a classification system for streets networks based on hierarchy and topology. He described the topology as 'patterns', and identified dominant patterns ranging from a cul-de-sac and loops dominant pattern with low connectivity, to a grid pattern with high connectivity, as shown in Figure 4.20.

4.5.1 Well-Connected network

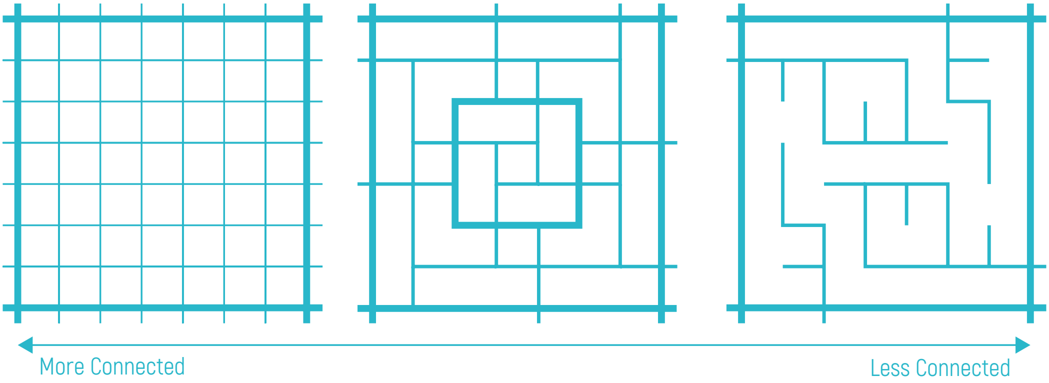
Advantages of a well-connected network

The more connected a road network is, the easier it would be to pool shared rides. NACTO's Blueprint for Autonomous Urbanism also recommends a highly interconnected grid network which can make the best use of transfers, allowing better connections between neighbourhoods and activity centres, and increasing capture area of transit (NACTO, 2017), as shown in Figure 4.21. An interconnected grid network with small block sizes is also considered more walkable and legible for pedestrians (Marshall, 2004). But well- connected network may lead to some unintended consequences. A large number of four-way intersections may slow down traffic (or pedestrians), depending on the intersection design strategy. Shorter routes may also create induced demand and generate more traffic. Additional regulations would need to be implemented to divert traffic from quieter areas in such networks.

Figure 4.19 Pedestrian crossing offset from the intersection

Source: SEH Inc.

Figure 4.20 Variations in network topology connectedness

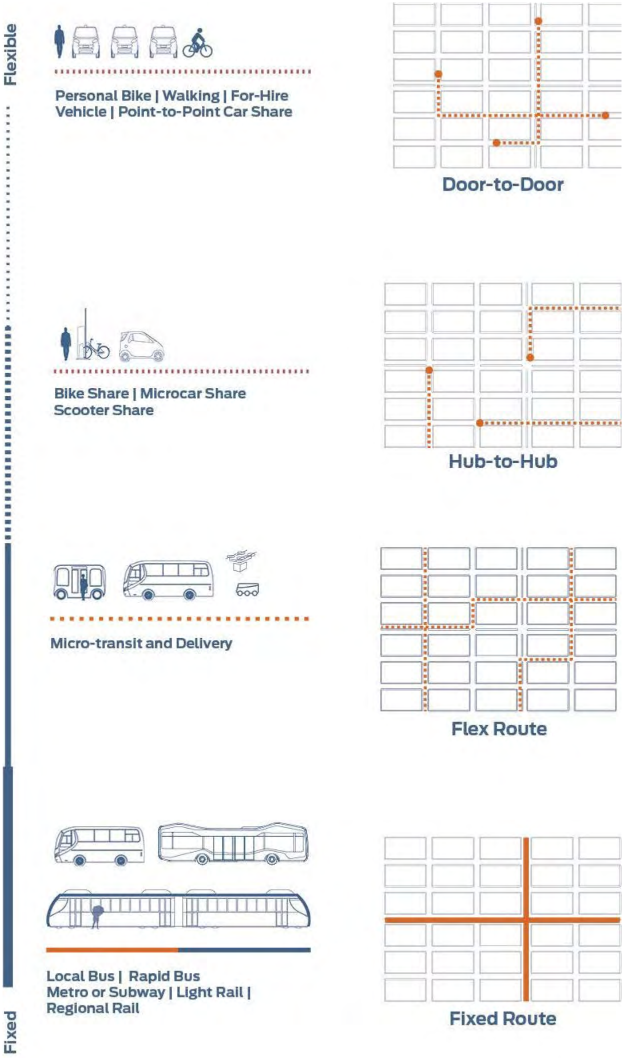


4.5.2 Disconnected Hierarchical Network

Origins and criticism

A highly hierarchical disconnected network is quite common in new large-scale developments in Asian cities. This pattern of development has its roots in car-based urban planning that began decades ago. In ***Traffic in Towns*** (1964), Buchanan argued for a highly hierarchical 'cellular' city, where major roads act as traffic distributors and enclose buildings served by minor access roads. This solution was a response to concerns regarding road safety and environmental quality but soon ended up generating even more traffic. Such networks cannot be served by public transit easily, due to lack of direct routes, which either increases the access distance to transit stops for pedestrians or increases the commute time. Dynamically routed shared automated vehicles could help improve access for pedestrians and transit users in such networks while safeguarding the environmental qualities and safety benefits argued for by Buchanan.

Figure 4.21 Flexible grid design
Source: (NACTO, 2017), p. 49



4.6 Some observations on design responses in practice

Best strategy cannot be determined

There is a wide range of design strategies that can be implemented in response to the technological shift. Here we have discussed strategies within five aspects of the urban form commonly dealt with in recent urban design proposals: street design, parking design, PUDO design, intersection design and network structure. While some of the strategies are a radical departure from the current convention, they do share some similarities with the grainy images of car-oriented cities from the first half of the twentieth century. Are we headed towards a familiar future, only in a higher resolution? Three observations can be made from the responses surveyed so far.

Small scale bottom-up transformations

First, in many of these images, the AV itself is pushed to the background, with a strong emphasis on multi-modality, people and public spaces which is a strong departure from the techno-deterministic point of view in early car-based imagery. The scale of the responses is also much smaller and local compared to the grand urban visions for the private automobile. Small scale targeted interventions and retrofitting of existing infrastructure are given priority, which points towards a change in thinking, from top-down technocratic urban interventions to bottom-up people-friendly urban transformation.

The interplay between transport and land use

Second, the interplay of transportation and land use is evident in many of these images, whether through responsive streets in Figure 4.10 or adaptable parking lots in Figure 4.17. The winners of Audi Urban Futures Award 2012, Howeler+Yoon, proposed public spaces that dynamically change use by the time of day and users, as shown in Figure 4.22. This image is drastically different from Corbusier's *La Ville Radieuse* (Figure 1.4), where home and work were separated through hard-edged highways. Both Corbusier and Howler+Yoon assume a certain amount of traffic flow and activity generation on the site for the success of their proposal, but both fail to quantify the nature of transport flows over time adequately. Lack of a quantitative time-based analysis can lead to gross under-utilisation of transport infrastructure or conversely, clog up the infrastructure, as is evident in modernist developments like Brasilia (Carroll and Phillips, 2008).

Strategies in conflict with one another

Third, the variety of interventions that can be made for different urban form aspects can conflict with one another. One clear point of contention is regarding the question of segregation by mode. The visions discussed in section 1.1 advocated the complete separation of the car from humans, but there is no such consensus in contemporary images for the technological shift, as seen in the range of responses in section 4.1.2 and section 4.4. Streets that are physically segregated by mode have not been very successful in reality, and at times been criticised for hampering active mobility and fragmenting the urban fabric. On the other hand, images showing harmonious mixing between all modes in a seamless environment have been criticised for over-estimating the capabilities of automation technology, reflecting a type of techno-optimism. How do we select an appropriate design intervention?

Intuitive conjectures not enough to understand complex systems

In order to purposefully restructure urban form to respond to the technological shift, the small scale urban interventions need to be unified into a holistic vision. Whether the selected design strategy would maximise the benefits of the technological shift or exacerbate its dangers, cannot be established through a purely intuitive test. The complex relationship between urban form and transport flows, leads to emergent effects that arise as a result of the process of self-organization in complex systems (Goldstein, 1999). These patterns of self-organisation cannot be understood through intuitive conjectures alone, and some degree of quantitative understanding is necessary to develop an informed design solution.

Quantitative modelling is not reliable in high uncertainty

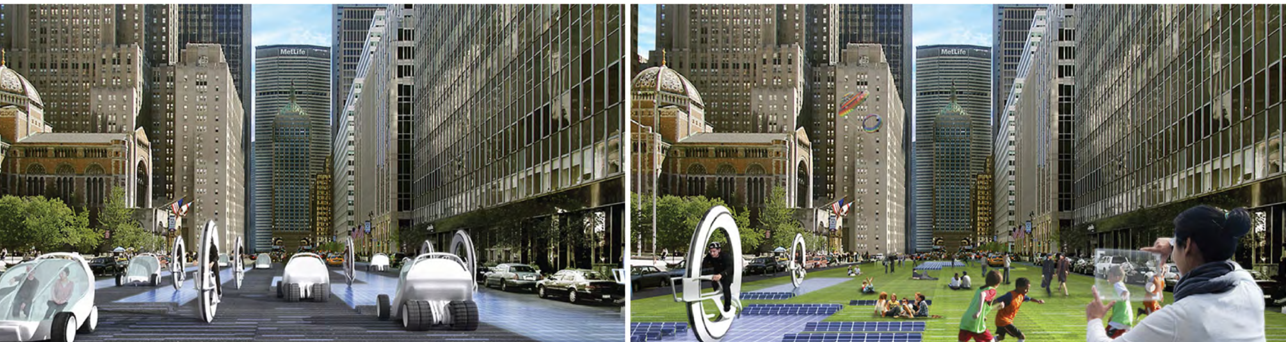
At the same time, one needs to be wary of purely quantitative modelling and analysis, given the uncertainty surrounding the technological shift and the difficulty in accurately modelling such complex systems. For instance, Alessandrini et al. (2015) find that higher densities and concentration of diverse activities are amenable to vehicle sharing. However, according to a mathematical model of Switzerland by Meyer et al. (2017), shared autonomous vehicles reduce travel times in low-density rural areas, but add additional demand and increase travel time in high-density urban areas. Such contrary findings indicate that purely quantitative modelling and analysis is also not sufficient to draw useful conclusions.

Combining quantitative analysis in urban design workflows

The challenge that faces us in determining an urban design response to the technological shift is to effectively include a quantitative understanding of transport flows in a typically intuitive urban design process. So far, planners have sought to transform cities by responding to changes in travel behaviour caused by external factors, such as a change in technology. Today urban design has a more ambitious behavioural goal of seeking to change travel patterns to steers the impacts of the technological shift towards a desirable future urban form. The complex two-way relationship between urban form and transport flows, and the uncertainty associated with the technological shift makes this task challenging. In the following chapters, we will unpack this complex relationship between urban form and transport flows, and urban design and travel behaviour, in order to build a methodological framework to conduct urban design in the context of the technological shift.

Figure 4.22 Dynamic use street

Proposal by Howeler+Yoon, winner of Audi Urban Future Award 2012 Source: (Heintz, 2012)



5 Relationship between Urban Form and Transport Flows

The impacts of the technological shift in transportation are highly uncertain. Under some conditions, it can support new, more liveable and sustainable urban models, while under others, it can promote existing unsustainable patterns of development. Can urban design influence the impacts of the technological shift? In order to address this research question. We will now build an overview of the relationship between urban design and transport flows in this chapter.

5.1 Static view of urban form and dynamic urban flows

Urban form as a Static observed by an object in motion

Urban form from the perspective of urban design is defined by the overall shape of the city, its built form and artefacts, which are intuitively considered fixed, static and durable. Although cities are sites of static structures, the solely morphological notion of cities has been continually contested. One line of thinking has explored urban form as sites of static structures observed through an object motion, exemplified by Corbusier's *'promenade architecturale'* (Samuel, 2010), which foregrounds the observer's pathway through built spaces. The *promenade architecturale* inspired urban designer Gordon Cullen to develop 'serial vision', a drawing of eight sequential views creating a dramatic itinerary, in his seminal work ***Townscape*** (Cullen, 1961). Similar explorations can be seen in the works of Venturi et al. (1977) and Appleyard et al. (1964).

Urban form and flows

Another conception of urban form beyond its morphological structure is expressed through the 'flows' that act upon it, animate it and transform it. Aldo Rossi (1984) summarises urban form through its 'urban artefacts', that may appear static, but are being "*transformed over time by forces acting upon them*". It was Lynch who first explicitly acknowledged 'moving elements in a city', or flows, as being as important as stationary physical parts, in his seminal book ***Image of the City*** (1960). He later expanded on this idea in ***Good City Form*** (1984).

> *"Settlement form usually referred to by the term 'physical environment,' is normally taken to be the spatial pattern of the large, inert, permanent physical objects in a city: buildings, streets, utilities, hills, rivers, ... I will take the view that settlement form is the spatial arrangement of persons doing things, the resulting spatial flows of persons, goods, and information, and the physical features which modify space in some way significant to those actions including enclosures, surfaces, channels, ambiences and objects."*

Theories on urban form in flows in geography and planning

It is now widely recognised that cities and regions depend fundamentally on flows and interchanges generated within them (Graham and Marvin, 2001; Jensen, 2009; Kropf, 2009; Wise et al., 2017). This conception of urban form that includes urban flows has significantly impacted urban theories regarding how cities function. For example, in geography this can be seen in the rejection of a sedentary view of the city and emergence of the *Mobility turn* at the beginning of the 21st century, pioneered by noted British sociologist John Urry. In urban planning, this view is exemplified by two prominent theories, Metabolist and Complexity theories.

Metabolism and complexity theory

Urban metabolism views the city as an organism, where resources flow in, circulate within and exit (Ravetz, 2000). Formative work on urban metabolism began in the seventies, but gained prominence after Kennedy et al. (2011) studied its applicability in urban planning and design. The *metabolist* theory was subsequently countered by *Complexity* theory. Where the former views the city as a closed system, the latter views it as an open one. In complexity theory, the city is seen as a system of linked decisions, such that a settlement grows as a cumulative product of decisions of individual actors. Although urbanists like Jane Jacobs and Christopher Alexander argued for such a complex view of the city already in the sixties and seventies, the works of scholars like Batty (2013), Hillier (1996) and Marshall (2004) in the last two decades have made strong links between complexity science and the practice of urban planning and design.

Transport flows and urban form relationship

Transport flows, defined by the physical movement of goods and people in the city, have a particularly strong influence on the urban form (Safdie, 1998). The physical movement required for people to conduct activities in different locations, which is determined by the urban form, generate transport flows. These flows have a strong spatial imprint that in turn, influences urban form. This complex reciprocal relationship between urban form and transport flows has been studied by several scholars. A seminal text on the influence of transportation on urban form and vice versa is ***Travel by Design*** (2001) by Boarnet and Crane. Other relevant literature exploring this relationship include ***Planning the Mobile Metropolis*** (Bertolini, 2017) and ***Streets and Patterns*** (Marshall, 2004). Evidence for the two-way relationship between urban form and transport flows is presented here based on selective literature in urban design and transport planning, analysed through four lenses:

- Transport Flows have a Spatial Imprint

- Urban Form Induces Transport Flows

- Altering Urban Design Alters Travel Behaviour

- Altering Transport Technology Alters Urban Form

5.2 Transport flows have a spatial imprint

Transport flows have a large spatial imprint

Transport flows have a substantial spatial imprint that we experience every day on our roads, bus stops or parking lots. Transport infrastructure in car-oriented cities can easily account for a quarter of its land area (Gössling et al., 2016). According to Rodrigue et al. (2013), this spatial imprint has five major components:

1. **Pedestrian areas**, or the space devoted to walking, which can account for 10-20% of the road's right of way.

2. **Roads and Parking areas**, which refers to the amount of space devoted to vehicular traffic, both in motion and parked. In a motorised city, on average 30% of the surface is devoted to roads and 20% for off-street parking.

3. **Cycling areas**, which often share space with pedestrian areas or road areas.

4. **Transit systems**, which may share road space with cars as with buses and tramways, or may have dedicated infrastructure, as with trains.

5. **Transport terminals** refer to the amount of space dedicated to terminal facilities such as bus stops, transit stations or airports.

Paths, movement spaces and armatures

Lynch (1960) developed the notion of '*paths*' that channel flows between '*nodes*' to define the spatial imprint of transport flows. The physical space that these 'paths' occupy is defined by Marshall (2004) as '*movement space*'. Streets are the primary movement space in cities and form a continuous network or continuum by which everything is linked to everything else. Shane (2005) interprets movement spaces as '*armatures*', which are infrastructure channels surrounded by fixed bounded sites or '*enclaves*'. While armatures are linear systems that sort and arrange urban elements, enclaves are bounded territories that adds friction to mobility. Paths, movement spaces or armatures link together nodes or enclaves in the city, making the transport network a fundamental organising feature of the physical form of the city.

Spatial imprint of flows

The spatial imprint of transport flows not only include the physical space that accommodates flows, but also the objects that constitute the flows. The Lynch-ian *path* is a physical channel through which "*people observe the city while moving through*". Jensen (2009) holds the view that "*people not only observe the city while moving through it, rather they constitute the city by practising mobility*". Similarly, Wall (1996) claims that "*the traffic of people, vehicles and information is also the environment and material of the city*". In this view, the spatial imprint of a six-lane urban arterial is different during peak and off-peak hours. The spatial imprint of transport flows can be defined beyond spatiality of the infrastructure, to include the spatiality of flows. Currently, urban design methods of analysis and representation focus on the former and neglect the latter. We will discuss this in more detail in section 6.2.

5.3 Urban form induces transport flows

Urban form, activity space and transport supply

Transport flows are a result of people's need to conduct activities at different locations, and in this sense urban form induces transport flows. Daily life revolves around friends, family, work, school, or shopping. The spatial distribution of these commitments/ opportunities is what Axhausen (2005) calls, the '*activity space*' of a person in his or her everyday environment. The size of the activity space is determined by the distribution of land use over an urban area. The larger the activity space, the more spatial interactions or 'trips' are required to overcome the distance between locations, leading to higher consumption of transport services.

Role of land use in transport

Urban form, through land use planning, plays a strong influencing role in transport planning. Banister (2005) lists six main categories of land use characteristics that determine travel patterns – the size of the settlement, intensity of land use and activities, mixing of land uses, decentralisation of activities, local accessibility to transport and parking provision. Engineers and planners use land use distribution as a basis to estimate trip generation rates and other travel behaviours, discussed in great detail in section 6.3.

Transport land use feedback cycle

Just as land use determines transport flows, transport flows influence land use patterns. The distribution of infrastructure in the transport system creates opportunities for spatial interactions, measured as 'accessibility'. The distribution of accessibility in space determines location decisions and hence changes in the land use system. In other words, people choose to locate their homes or businesses near potential destinations like a train station. This complex and dynamic link has been widely described as the '*transport land-use feedback cycle*' (Kasraian et al., 2016; Kelly, 1994; Wegener and Fuerst, 1999).

5.4 Altering Urban Design Alters Travel Behaviour

Existing Literatures Reviews

Urban design influences travel behaviour, which is a primary inference based on which we seek to change travel patterns and steer the impacts of the technological shift towards a desirable future urban form. Several studies in transport planning have investigated this correlation. Boarnet and Crane discuss at length the influence of urban form on travel in ***Travel by Design*** (2001). An international review by Stead and Marshall (2001) evaluates empirical studies on urban form and travel patterns over twenty years. Eran Leck (2006) conducted a statistical meta-analysis of studies on the impact of urban form on travel behaviour, specifically in New Urbanist developments. Ewing and Cervero (2001) reviewed studies that analyse the effects of the built environment on travel choices, based on which they identify six broad urban design areas of influence – density, 'mixity', network structure, access to transit, parking and human-scale design features.

Density

The density of urban form determines the concentration of activities and size of the spatial barrier between them. Boarnet and Crane (2001) and Leck (2006) both identify residential and employment densities as the most influential built environment element with respect to travel choices. Ewing and Cervero (2001) and Leck (2006) find that employment densities are more significant than residential densities. Although high density is known to reduce travel distances and influence mode choice, according to Ewing and Cervero (2001) density on its own is not a beneficial indicator, without its regional context. For example, dense, mixed-use developments in the middle of nowhere may offer only modest regional travel benefits. Stead and Marshall (2001) instead consider 'location' with respect to existing towns or infrastructure in combination with 'settlement size' or compactness.

Mixity

The second crucial influencing factor is 'mixity', which Boarnet and Crane (2001) define as the 'extent of land use mixing' and 'jobs/housing land use balance'. Although mixing of activities affects the physical separation between activities, hence influencing travel patterns, Stead and Marshall (2001) find evidence that suggests that mixity is not as important an influencing factor as density. An aggregate measure of land use mix (termed 'diversity') is examined by Cervero and Kockelman (1997) who report a link between land use mix and non-work travel, but no link between land use mix and total distance travelled. On the other hand, Leck (2006) finds that the influence of land use mixing on travel is overwhelmingly significant. Both density and mixity have not been adequately explored in practice as a purposive urban design strategy to influence travel patterns in the context of the technological shift.

Network structure

The third influencing factor is the street network, which is characterized by street connectivity, the directness of routing, block sizes and sidewalk continuity. Streets are the fundamental organising feature in cities, and street network topology has far-reaching impacts on travel patterns. It is also especially influential in determining the success of ride-sharing systems, and one of the areas of urban design intervention in response to the technological shift, as discussed in section 4.5. In their review, Stead and Marshall (2001) find that while it is not easy to single out the effects of road network type on travel behaviour, there seems to be an inverse relationship between the attractiveness of a mode and the distance travelled by that mode. For example, a grid layout may promote short and direct routes for either pedestrians or car traffic, leading to less or more vehicle kilometres travelled, respectively. Ewing and Cervero (2001) also find several studies in their review that report a significant relationship between travel and network design, but Leck's (2006) meta-analysis finds the linkage between these two elements insignificant.

Transit accessibility

Access to transit, through the location of transit stops or highways, is also an important influencing factor. Access to transit is especially critical in the context of the technological shift and has been explored in various urban design responses in practice, as discussed in section 4.3. According to Stead and Marshall (2001), better access to more transport networks – road or rail – increases travel speed, extending the distance that can be covered. Cervero (1994) finds that the proportion of rail journeys decreases with increasing distance from the railway station in California, and observes similar patterns in Washington, Toronto and Edmonton. However, Stead (1999) finds little evidence in Britain of a link between the proximity of homes to a railway station and travel distance.

Parking

Given the central role of the private automobile in urban transportation, parking is an important influencing factor, in terms of both supply and location vis-à-vis streets and buildings (Ewing and Cervero, 2001). It is also an important area of urban design response reviewed in section 4.2 Large expanses of suburban parking lots can create spaces that remain unused most of the day. On-street parking may conflict with flows of cyclists or transit. Just as proximity to transit station might increase the probability of transit use, availability of parking may encourage car use. Stead and Marshall (2001) report in their review that as the availability of residential car parking increases the proportion of car journeys increases.

Human-scale design features

Lastly, 'human-scale design features' can have a strong influence on walkability and mode choice, and consequently, overall travel patterns. The responses to the technological shift in urban design practice also tend to be small scale and targeted at improving pedestrian experience, as discussed in section 4.6. Small scale design interventions that target improvements in walkability are grouped under various nomenclatures, such as 'pedestrian features' (Boarnet and Crane, 2001), 'urban design variables' (Ewing and Cervero, 2001), neighbourhood type (a composite of age and style of development and street network type) (Stead and Marshall, 2001) or simply 'design' (Cervero and Kockelman, 1997).

Influence of urban design alone is minimal

Intuitively, Ewing and Cervero (2001) find that urban design is likely to have only a marginal impact on primary trips (e.g., whether and how to get to a particular destination), but would be more significant for secondary trips (trips within an activity centre that can be made either on foot or by car). In their review, they find that individual urban design features are mostly insignificant, but become significant when combined with other features, such as pricing. They combine different urban design features into composite measures, as shown in Table 5.1.

Walkability and urban design

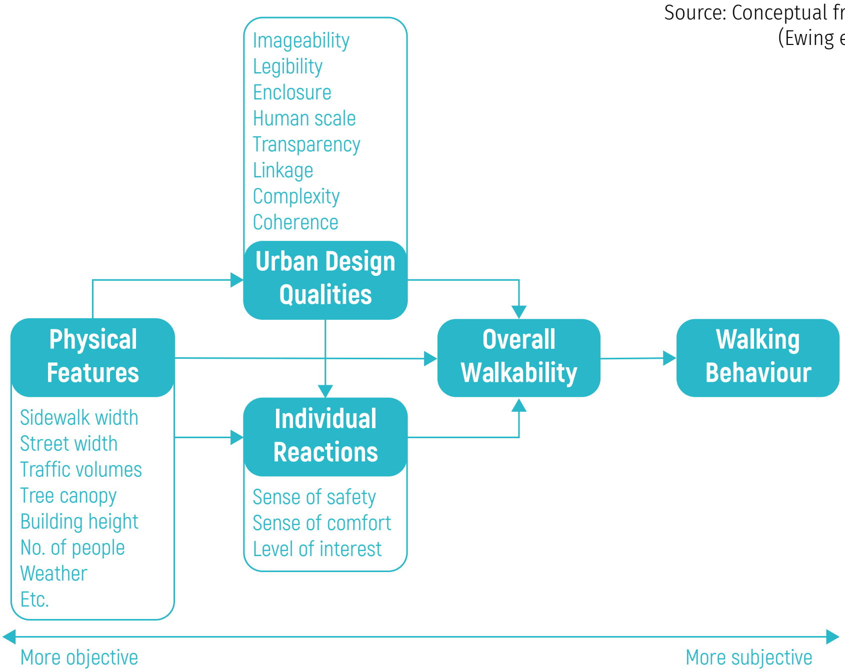
The influence of urban design features on active mobility – walking and cycling, is much more significant than that on overall travel behaviour, according to most of the literature surveyed. Ewing et al. (2006) developed operational definitions and measurement protocols for essential urban design qualities of streetscapes associated with walkability, as shown in Figure 5.1. Pikora et al. (2003) developed a framework for potential environmental influences on walking and cycling based on published evidence, policy literature, interviews with experts and a Delphi study. They found that street width, maintenance and continuity of street, traffic volume, design of streets, intersection and access points, aesthetics of streetscape, among others, have a significant influence active mobility.

Table 5.1 Composite Land Use Urban Design Variables

Independent Variables	Principle Component
Office within 0.25 mile of site Residential development within 0.25 mile of site Retail development within 0.25 mile of site Personal services within 0.25 mile of site Open space (parks) within 0.25 mile of site	Mix of Land Uses
Restaurants within 0.25 mile of site Banks within 0.25 mile of site Child care within 0.25 mile of site Dry cleaner within 0.25 mile of site Drug store within 0.25 mile of site Post office within 0.25 mile of site	Availability of Convenience Services
Presence of four or more services Frequency of certain services Presence of sidewalks Traffic Volume Transit Stop	Accessibility of Services
Absence of vacant lots Pedestrian activity Sidewalks Street Lighting	Perceived as Safe
Absence of graffiti Presence of trees and shrubs on sidewalk Wide sidewalks Minimal building setbacks	Aesthetically pleasing

Source: (Ewing and Cervero, 2001), Table 6, p. 106

Figure 5.1 Urban design qualities related to walkability
Source: Conceptual framework adapted from (Ewing et al., 2006), Fig. 1, p. 225



Limitation of Quantitative methods to study urban design and transport

While most studies seem to suggest that human-scale design features influence travel behaviour, especially for active mobility, they are unable to attribute changes in travel behaviour to any specific design element. Stead and Marshall (2001) attribute these difficulties to the ambiguities in the descriptions of design, which cannot be adequately represented in quantitative studies. Næss (2015) believes that neo-positivist studies that highlight correlations and invariances rarely reflect on the nature of causal influences. He proposes a combination of qualitative and quantitative research methods instead, to break out this 'regularity-seeking' tradition towards an 'interpretivist' tradition. This criticism is addressed in more detail in section 7.1.

Design approaches

Parallel to these quantitative studies, several urban design and planning ideas emerged in the eighties and nineties that normatively reflected on the relationship between urban form, scale and movement. In a review of urban planning and design literature, Jabareen (2006) found four models of sustainable urban form, of which *New Urbanism* or, *Neo-traditional* developments were found to be most prominent. New urbanism, emphasizes certain concepts of sustainable urban form such as pedestrian-friendly design and walkability, high density, compact development and mixed-use (Congress for the New Urbanism, 2000).

Debates on the effectiveness of New Urbanism

The effectiveness of New Urbanist design features to influence travel behaviour positively has been a subject of considerable debate. For example, a simulation study confirmed that a connected or grid street design of new urbanist neighbourhoods reduces VKT (McNally and Ryan, 1992). However, an empirical model built by Crane and Crepeau (1998) found that street pattern has no significant effect on car or pedestrian travel when controlling for land uses and densities around the trip origin, trip costs, and traveller characteristics. Similarly, some scholars criticise compact developments, citing problems such as overcrowding and social inequity (Burton, 2000; Gordon and Richardson, 1997; Neuman, 2005). Despite criticisms, there seems to be a general agreement on the principles of urban design and transportation promoted by New Urbanism (Ellis, 2002), and urban designers regularly employ these intuitive normative principles in design practice.

5.5 Altering transport technology alters urban form

Transportation technology impacts urban form

In the past century, transformations in urban form have been linked to some kind of transport revolution, as discussed in section 1.1. The introduction of streetcars, commuter trains, automobiles and freeways, all dramatically altered the shape of the city. Among the most fundamental changes in the urban form resulted from mass automobilisation. Its effects included emergence of new clusters of urban activities and new relationships between elements of the urban system, such as the dispersion of settlements, suburbanisation and urban sprawl (González-González et al., 2019; Rodrigue et al., 2013).

Theory of travel time budget

The expansion of urban footprint as a result of the growing use of cars can be explained by the idea of '*time budgets*' (Hägerstraand, 1970). According to this theory, individuals command '*action spaces*' of different size and duration based on time and monetary budget, and institutional regulations, leading to specific '*space-time paths*' as shown in Figure 5.2. Speed improvement and cost reduction in transport lead to faster and longer trips, impacting the spatial structure (Wegener and Fuerst, 1999). This expansion of spatial structure was categorised by Adam (1970) into four transportation eras as shown in Figure 1.2.

Path dependence of urban form

If higher speed results in a separation of activities and changes arrangement of settlement, vehicle automation could be expected to further this process of expansion. Drawing such simplistic conclusions can be deeply flawed since the evolution of the urban form is path-dependent. The current spatial structure is the outcome of past developments and is related to unique local conditions. Diverging ways in which people use transportation around the world means technologies can be implemented in dramatically different ways, aiding or hindering the production of desirable urban environments (Freemark and Zhao, 2018).

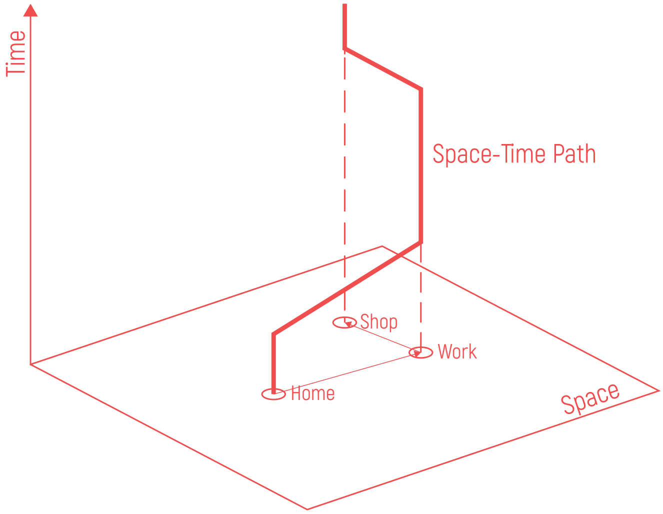


Figure 5.2 A space-time path representing activity space
A continuous trajectory of a person's daily movement in space and time. The vertical axis represents the temporal progression and the horizontal plane represents the geographical extent of a person's activity space.
Source: Adapted from (Hägerstraand, 1970), Fig. 2, p. 14

5.6 In summary

What the two-way relationship means for the technological shift

There is a strong two-way relationship between urban form and transport flows. The influence of changes in transport flows on urban form reiterates the importance of including transport analyses in urban design processes. On the other hand, the capacity of urban design to influence travel patterns compels the discipline to respond to the technological shift in order to nudge its impacts and produce desirable future urban forms. However, both these goals have been difficult to implement in practice.

How can urban design play a purposive role

Urban design must play a more purposive role in influencing the technological shift, but historically planners have rarely sought to change urban form to influence travel patterns. The utopian visions in response to the automobile revolution may at first seem contrary to this assertion, but the debates and decisions about a city were primarily deferred to road engineers at the time, and the goal of urban planning was only to accommodate the car (Boarnet and Crane, 2001). In recent times urban designers and planners have begun to recognise the role of urban form in influencing travel behaviour. The next chapter discusses this evolution through a review of the methodological relationship between urban design and transport analysis.

6 Methodological Relationship between Urban Design & Transport Planning

We need to build a better understanding of the cause and effect mechanism behind the design strategies discussed in Chapter 4, by integrating urban design and transport analysis. The methodological relationship between urban design and transport planning has been evolving continually, knitting the two more tightly together over time. This chapter addresses the methodological debates and techniques used in urban design and transport planning.

The two disciplines are typically linked through the 'predict and provide' process, which often results in a 'disciplinary apartheid' between urban design and transport planning. This disciplinary apartheid is especially problematic in the context of the technological shift, given the strong two-way relationship between urban form and transport flows, discussed in the previous chapter. Here we develop a critique on the predict and provide process, through a discussion on methods in urban design and transport modelling.

6.1 Predict and Provide

Disciplinary apartheid

Traditionally urban form has been the mainstay of urban design and planning disciplines and transportation flows that of transport planning and traffic engineering. Despite the strong relationship between built form and transport flows discussed in the previous chapter, these two aspects of cities are studied in very distinct traditions, with very little interaction between them, typically linked through a 'predict and provide' process. Traffic flows are predicted in transport planning through quantitative modelling and these predictions are used as a starting point in urban design to provide infrastructure using normative design principles.

Beginning of predict and provide

'Predict and provide' approach became popular in the sixties and seventies when planning for transportation was mostly driven by transportation engineers following a distinctly mechanistic approach. The idea that transport planners could not directly manipulate urban form was embedded in this approach (Boarnet and Crane, 2001), leading some scholars term this process as 'predict and accommodate' instead (Rodrigue et al., 2013). Isserman (1985) in his seminal essay 'Dare to Plan', bemoaned planners' over-reliance on mechanical forecasts and the diminishing role of planning in shaping urban development. As it became clear that the predicted mobility demand may be impossible to meet, and could even be destructive to the urban fabric, scholars and practitioners proposed alternatives to the predict and provide approach.

Alternatives to predict and provide

New ideas such as 'predict and prevent' (Owens, 1995) and 'decide and provide' (Lyons and Davidson, 2016), called for the inclusion of planning and design as deliberate action rather than passive provision. The former, also known as 'transport demand management' and has since been criticised for ignoring the degree to which rapid mobility contributes to society's well-being (Bertolini, 2012). The latter has been criticised for underestimating the challenges of building consensus on a decision for deliberate action, given the multitude of interests and actors.

Predict and provide remains dominant

Today 'predict and provide' remains the mainstay of the urban design-transport planning link (Goulden et al., 2014; Næss et al., 2014). However, methods of prediction within transport planning and provision with urban design have evolved considerably, gradually narrowing the gap between the two disciplines. Urban design increasingly incorporates more functional descriptions of transport flows, and transport models include increasingly finer-grained descriptions of urban form. The following section presents a cross-disciplinary review of methods of prediction and provision in and transport planning and urban design.

6.2 Urban design methods to analyse transport flows

Physical models in urban design

Urban design discipline relies heavily on physical representations to communicate ideas of scale, form and structure, but due to their static nature they under-represent transport flows. Elements of transport flows such as vehicles and pedestrians may be represented as objects, but the temporal qualities of flow such as speed, are not communicated.

Digital models in urban design

The rise of computers in architecture from the 1980s onward brought about a fundamental change in architectural modelling. Initially, computers were only used for digitising conventional drawings and models, but in recent years we see a rise in planning support systems (Geertman and Stillwell, 2009) that allow better representation and analysis of urban flows. Here we discuss three such analytical approaches – typological, network-based, and parametric.

6.2.1 Typological approach

Architectural view of streets

Typological studies are one of the most common methods to analyse transport flows in urban design. Typically, aspects of urban form are identified as *types,* (Kropf, 2009), and function is only implicit in the *type*. Street typologies define street as architecture, either (a) in a plan, as space between buildings, (b) as a street section, or (c) as street frontage or city block elevation. Such typological studies of streets can be found in seminal works such as (Appleyard et al., 1981) and (Jacobs, 1995).

Functional role of streets

A major drawback of solely relying on this view of streets as architecture is what Batty and Marshall (2012) call, 'physicalism', the assumption that physical form is the appropriate way to represent cities. Non-physical interactions are not adequately represented and therefore, under-analysed in this approach. Street typology definition can be extended from its architectural to its functional role, by using a classification based on use (users, traffic volume, trip length, transport modes), structural role (spine, connector, cul-de-sac), strategic role (link road, local road), or designations (ownership, speed limit, user permission) (Marshall, 2004).

6.2.2 Network-based approach

GIS and morphological analysis

In a network-based approach, every element of the design is geometrically represented as points, lines or polygons. The geometry is linked to data columns which carry desired information, such as speed limits, mode restrictions, or other non-physical typological descriptions. Usually, the street network representations are located in a geographic space where GIS-based analyses can be performed. For instance, metrics such as accessibility to services can easily be tested in a GIS model of the network (Sevtsuk, 2014). Function, which was implicit in the typological approach, is made explicit in such GIS-based models.

Space syntax and configurational analysis

Configurational analysis is another increasingly popular network analysis approach, where street networks are not represented morphologically, but as graph networks. Graph-theoretic principles have been applied to study transport networks for a long time, such as Kansky's (1963) indicative indices for transport network connectivity. However, it was only after the development of user-friendly 'Space Syntax' tools by Bill Hillier's team at UCL, that these methods became accessible to urban design practice. Space syntax describes how the configuration of spaces relates to how people perceive and move through them (Karimi, 2012). Unlike GIS-based network analyses, space syntax focusses entirely on streets and their configuration, and not the buildings they access.

Problems with network-based approaches

Both morphological and configurational approaches to network analysis rely on the principle that the efficiency of the network depends solely on the layout of network links and nodes. Network structure affects accessibility to a large extent, but externalities such as cost, congestion, service levels of public transport, and temporal variations have a strong impact as well, which is ignored in this approach.

6.2.3 Parametric approach

Parametric and procedural modelling

In the parametric approach, the form is defined by the relation between specific parameters of the form. It is a widely used method in architecture and urban design research and practice, made popular with the availability of commercial tools such as Grasshopper for Rhinoceros and ESRI CityEngine (Parish and Müller, 2001). Sousa and Celani (2018) systematically mapped several existing studies that use generative, parametric and procedural urban modelling to explore the relationship between urban design and travel demand. For example, Aschwanden et al. (2011) combined CityEngine with a commercial agent-based crowd simulation tool called Massive Software to visualize interactions between the built environment and travel behaviour. Koltsova et al. (2012) translated urban design qualities that promote walkability into parameters to generate urban spaces using Grasshopper for Rhinoceros.

Advantages and disadvantage of parametric modelling

Parametric models make the relationship between urban structure and buildings explicit through the definition of rules. The translation of 'fuzzy' urban design elements into clearly defined parametric relations makes the design mathematically manageable, allowing better integration with transport models. However, such a translation poses the risk of over-simplification of complex design elements or conversely, the definition of too many parameters for the sake of realism, making the model computationally unmanageable.

6.3 Evolution of transport modelling

Transport models

This section traces the evolution of modelling methods in transport analysis and their view of urban form. Transport models are based on mathematical and econometric theories to produce quantitative predictions of traffic flows. Models were first developed as a branch of transport engineering, but are now a fundamental tool of analysis for transport planning and land use forecasting. While the quantitative model has remained the mainstay of transportation flow prediction since the early fifties, methods of modelling and simulation have evolved significantly, in response to paradigm shifts in transportation.

Paradigm shifts in transport planning

Paradigm shifts in transportation planning have influenced methods of prediction and evaluation. According to Litman (2013a), a paradigm refers to the underlying assumptions used to define a problem and to evaluate solutions. As a discipline's paradigm shifts, practitioners need to re-examine their assumptions and analysis methods. Here we discuss four crucial transport planning paradigms and modelling methods: traffic based planning and aggregate modelling, travel demand management and disaggregate modelling, planning for accessibility and activity-based modelling, and people-centred planning and agent-based modelling. Since there is no clear dividing line between different paradigms, as shown in Figure 6.1, several methods and paradigms co-exist in one moment in time.

6.3.1 Traffic based planning and aggregate models

Traffic based planning

The earliest transportation models were based on a traffic-based planning paradigm, that focused on accommodating the 'inevitable' growth in automobile traffic. This planning paradigm tended to favour large scale interventions to reduce travel times and maximise street capacity. Such interventions require a more strategic approach and involve major public investment, which made mathematical analytical techniques popular at the time (Jones, 2014). Transport models were built based on a positivist outlook, with the belief that the relationships found in natural science, such as gravitational attraction, could be extended to urban systems (Kane and Behrens, 2002).

Gravity model

Aggregate models were one of the first models used to predict travel demand and identify planning options by aggregating flows of traffic between origins and destinations through gravity models (a type of spatial interaction model, see (Hayes and Wilson, 1971)). Gravity models are based on the principle that the frequency of interaction between two zones is directly proportional to their size and inversely proportional to the distance between them, also known as Tobler's first law of geography (Tobler, 1970). These models are operationalised through a series of rigorous steps, called the 'four-step process', shown in Figure 6.2.

Four-step process

In the four-step process the study area is first divided into zones, and then total trips (or transport flows) are generated for each zone (Trip Generation). These flows are then distributed between zones based on a gravity model (Trip Distribution). The flows are then split by mode using statistical models (Modal Split), and finally, resultant flows are assigned to the network (Network Assignment). In this way, the total network provision required can be calculated. The predictions of future traffic flow produced by this 'four-step process' often resulted in a demand for increased infrastructure provision and expansion in capacity, since predictions are typically based on extrapolating current trends.

Urban design and aggregate models

As gravity models became commonplace in transport planning, distance became the key organising factor of transport flows (Wise et al., 2017), but at a very low spatial resolution. Complex urban elements were abstracted out and consolidated into large aggregated zonal data. Alternative destinations choices were also not considered so that there is no competing destination (Hensher, 1977). A lively street with multiple shopping options is treated the same as a purpose-built shopping mall with the same square meters of retail, in terms of how many trips it attracts.

Time and human behaviour in aggregate models

Aggregate models are based on the assumption that cities are in equilibrium (Wise et al., 2017) when, in reality, they are far from it. Urban processes are dynamic with different speeds and response times, which is not well-represented in aggregate models. The temporal resolution of these models is low, and only the total number of peak hour trips are taken into consideration. These models also conceal individual behavioural differences and biases. Households within a given spatial zone are considered to be homogenous. The only variable explaining spatial location behaviour in the model is generalised transport costs, rendering details of urban form insignificant.

Brotchie triangle

Urban design was a young discipline when aggregate transport models came into prominence in transport planning, and the two have very little interaction. Even so, aggregate models made significant contribution to building an initial understanding of the urban form and mobility relationship. Brotchie (1984) spatialized the gravity model in the 'Brotchie Triangle', which represents the universe of possible configurations of spatial interaction (represented as mean travel distance to work) and spatial structure (represented as spatial dispersal). Depending on the type of transportation system, network topology, density, and existing infrastructure, the city may move in any of the three directions, as illustrated in Figure 6.3.

This foundational understanding of the relationship between transport flows and urban form can help us make useful conclusions regarding how the improvement in vehicle speed and efficiency due to automation may impact overall urban footprint. However, the low spatial and temporal resolution of aggregate models makes them inadequate to study the dynamics of individual design strategies and their impact on transport flows.

Figure 6.1 Evolution of Transport Planning Paradigms

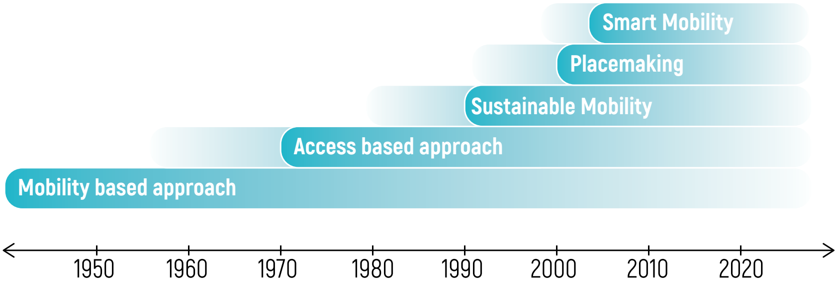


Figure 6.2 Four-step process in Aggregate Models

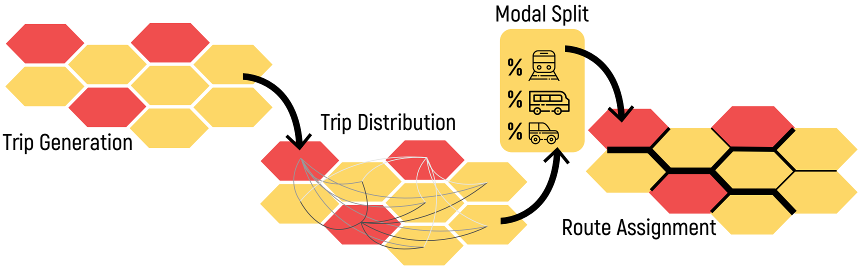


Figure 6.3 Brotchie Triangle
Adapted from (Brotchie, 1984), Fig.3, p 586

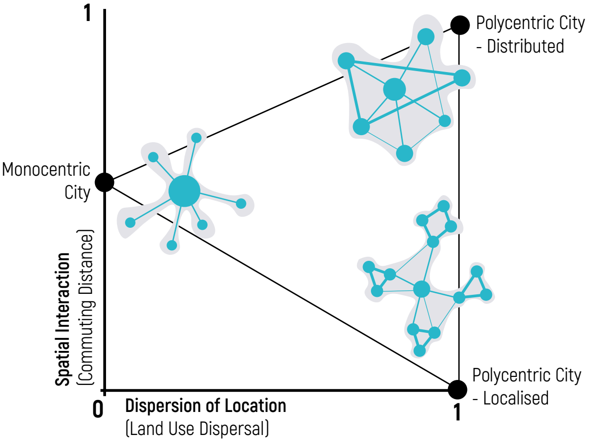
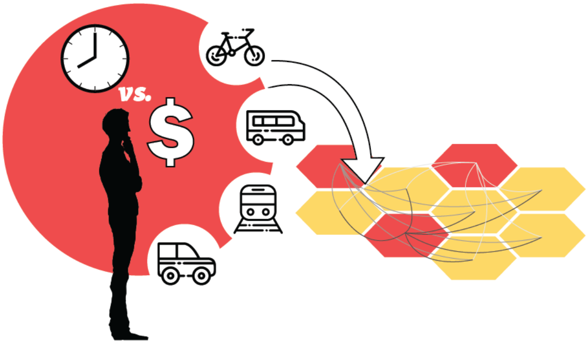


Figure 6.4 Disaggregate model and the four-step process
Disaggregate models consider discrete choices for travel mode and aggregate them in a four-step process.



6.3.2 Travel demand management and disaggregate models

Emphasis on mode shift

In the sixties and seventies, transport policy shifted from a vehicle-based perspective which encouraged traffic infrastructure expansion, to travel demand management by encouraging a modal shift towards public transport, which use limited urban space to move people more efficiently than private cars (Litman, 2015b; Walker, 2012). Although modal shift from car to other modes of transport was encouraged through policy, there was no significant cutback in provision for cars (Jones, 2014).

Disaggregate models

Aggregate models assume homogenous behaviour across all individuals in a zone, making it challenging to test policies regarding travel demand management and modal shift. The emergence of disaggregate travel demand models, which are concerned with discrete choices of an individual, such as choice of residential and business location, automobile ownership or when to make a trip (see Figure 6.4), helped to address this issue better. The early disaggregate models followed a trip-based approach, where a single trip was the basis of analysis.

Discrete Choice Analysis

In order to implement an individual's mode choice in disaggregate models, discrete choice analysis is used. *Discrete choice analysis* describes, explains, and predicts choices between two or more discrete alternatives. It is a concept based on *random utility theory,* borrowed from behavioural economics, where individuals are assumed to always select the alternative that maximizes their utilities (Domencich and McFadden, 1975), which in the case of transportation is usually a representation of time or money saved. The choice made by each person is statistically related to their attributes and the attributes of the alternatives available them. The model then estimates the probability that a person chooses a particular alternative (Ben-Akiva et al., 1985), which allows us to answer questions such as, if a middle-income person owns a car and lives near transit, how likely is she to use transit if fuel prices rise by a certain amount?

Trip based disaggregate models vs aggregate models

There are some similarities and differences between disaggregate models and aggregate models. Trip-based disaggregate models cluster trips by motive (going to work, or shopping), to derive the expected trip frequency of each individual based on probabilistic discrete choice models. The expected trip frequency of each individual is computed and added across all individuals to give the total aggregate travel demand for every zone. Conversely, in an aggregate model, the trip frequency of the 'average traveller' in a zone is multiplied by the population of the zone (Hensher, 1977). Similar to aggregate models, once the trips are generated in a disaggregate model, they are aggregated by zone and then used to predict transport flows through assignment, using a 'four-step process' (Figure 6.2).

Urban form and trip-based models

Discrete choice theory provides a framework for thinking about the causal relationship between urban form and travel behaviour. Urban form can also be evaluated in terms of the sets of choices it provides, for example, a walkable street may add a positive utility and high-speed traffic may be seen as a disutility when determining the probability of selection of walking as a mode choice. Although researchers have used discrete choice theory extensively to study the relationship between individuals and their travel behaviour, they have used it in only a very limited way to explore the relationship between the choice set that urban form provides and travel behaviour (Handy, 1996).

Criticism of trip-based models

Disaggregate models integrate behavioural and economic models to refine predictions at the individual level, but their spatial resolution remains highly aggregate. Disaggregate models do not consider mutual dependence between trips, people and activities (Iacono et al., 2008; Wise et al., 2017). They ignore diversity among individuals and urban form aspects, which are either treated as exogenous or highly simplified (Zhang and Levinson, 2004). The treatment of space and form as a simple choice variable in a utility calculation is severely limiting (Torrens, 2003). The urban design strategies discussed in Chapter 4, present choice categories with fuzzy distinctions rather than discrete. The temporal resolution remains low as well since the models are static and forced to reach a general equilibrium (Iacono et al., 2008). These issues limit the applicability of trip-based disaggregate models to study the impact of design strategies in the context of the technological shift.

Figure 6.5 Diagram to conceptually describe an activity-based model
Activity-based models take into consideration daily activity schedule of an individual over time, distributed in space, even at the scale of a building with different uses as indicated by the colours.

6.3.3 Planning for accessibility and activity-based models

New paradigm – from mobility to access

The transport planning paradigms we discussed so far were more or less based on the principle of mobility as the primary goal of transportation, whether by car or transit. They aimed to maximize travel distances within minimum time and money budgets. In reality, mobility is seldom an end in itself, and travel mostly is a 'derived demand'. This led to an 'access-based' understanding of transportation (Litman, 2013a) where the primary goal of transportation is access to services in order to perform activities. In the seventies and eighties, policies to reducing the length of trips through greater efficiency in the transport system and land use planning began receiving more attention (Papa and Lauwers, 2015).

Activity-based modelling

As transport planning shifted focus from mobility to prioritising access to services to perform activities, the techniques for transportation modelling also evolved followed suit. Activity-based approaches to transport modelling emerged, that described decisions concerning activities people pursue given a fixed land use, transportation supply, and individual characteristics. Figure 6.5 diagrammatically shows how individual's activities are scheduled in time and space.

Activity schedules

The activity schedules emerge from an interrelated set of decisions for each activity, regarding whether, where, when, for how long and with whom to participate, which in turn affects the travel demand (Axhausen and Gärling, 1992). From this vast choice set of various activity patterns, an individual selects the patterns that maximise her utility (based on random utility theory), by solving a large-scale combinatorial optimization problem conditional on others' decisions (Zhang and Levinson, 2004). The classic four-step process discussed in section 6.3.1, cannot manage this complex problem of determining optimum activity patterns based on inter-dependent individual choices. Activity-based multi-agent simulations were developed in the nineties that were much better suited for this purpose.

Five assumptions of activity-based models

Activity based models represent a shift from aggregate quantities and relationships to disaggregate ones, based on five assumptions. The first is that travel is a derived demand, and not an end in itself (except a tiny percentage of trips – see (Mokhtarian and Salomon, 2001)). The second is that the ability to perform an activity is dependent on its availability, in both space *and* time (see space-time geography illustrated in Figure 5.2). Third, a 'trip' is the result of connecting two spatially separated sequential activities. Fourth, travel needs to be regarded in the context of interdependencies in 'activity chains' (Jones et al., 1983). If more time is spent on one activity, less is available for others. Finally, activity chains are a result of an 'activity scheduling process', which includes decisions about which activities to perform, where, when, for how long, through what mode and route (Doherty and Axhausen, 1999).

MATSim

Axhausen's (1988) pioneering work in activity chains and travel behaviour modelling coupled with a mesoscopic traffic simulation has been furthered through the open-source MATSim (Multi-Agent Transportation Simulation) project, considered state of the art in the field (Bazzan and Klügl, 2014; Rasouli and Timmermans, 2014). The simulation framework is based on a co-evolutionary principle, where a collection of autonomous decision-making entities called *agents*, reside in an *environment* and make decisions based on a set of *rules*. (Horni et al., 2016). The empirical part of this research relies heavily on the latest developments in MATSim, which is discussed in greater detail in section 8.4.

High temporal resolution of multi-agent simulations

Activity-based multi-agent simulations offer higher spatial and temporal resolution as compared to aggregate, and trip-based disaggregate models. While the latter analyses transport flows across one cross-section in time, multi-agent simulations are dynamic, and model transport flows over time. In other words, multi-agent simulations are '*a method to exercise the disaggregate model over time*' (Miller, 2003). The higher temporal resolution also makes the model more sensitive to predicting the impacts of new transport policies, such as controlling emissions and managing travel demand in off-peak hours (Rasouli and Timmermans, 2014).

High spatial resolution of multi-agent simulations

The *agents* in multi-agent simulations operate in an environment, which can be seen as a proxy for the urban form. Emergent transport flows constantly modify the characteristics of the environment, bringing flows and form in close dialogue. While the conceptualisation of urban form in earlier models was a more abstract, geographic representations of zones or census tracts, in multi-agent simulations we find much more detailed geometric representation of buildings, parcels, and streets (Batty, 2017), as shown in Figure 6.5. Multi-agent transport models have also spawned extensions to land use modelling, fusing ideas about density, rents, housing markets and locational decision-making (Wise et al., 2017), such as UrbanSim (Waddell, 2002). The temporal and spatial resolution of multi-agent simulations makes it more suitable to study the impacts of design strategies on transport flows.

6.3.4 People-centred planning and agent-based models

People-centred planning and ABM

As activities and land use planning started getting more attention in transport planning, it led to a growing interest in public spaces and streets as a place for activities. People-centric approaches in transport policy became prevalent by the early 2000s, for example, classification of streets based on movement and place function in London (Streetscape Guidance, 2019), instead of the conventional categorisation based on speed of traffic or lanes. While activity-based multi-agent models have a high spatial and temporal resolution, they are not able to encapsulate the fine-grained interactions of transport flows, which become more relevant at the scale of a pedestrian. For example, the type of pedestrian flow observed on the street with high place function (based on London's classification system) will be very different from that on a street with high movement function.

Defining Agent-based models

Agent-based models (ABM) can directly address these shortcomings due to their focus on individual behaviour by addressing the movement of persons and the way they interact with each other. ABM breaks a system down into individual actors, or agents, which interact with their environment, much like multi-agent simulations, but also with one another, based on their own individual attributes and behavioural rules. The autonomous and social features of agents allow complex, nonlinear interactions between them to be modelled, which leads to collective behaviours and emergent phenomena such as self-organization (Chen, 2012).

ABM and pedestrians

An important application of ABM is pedestrian modelling (see social force model for pedestrians by Helbing and Molnár (1995)), which enables us to study crowding, flocking, and herding effects that emerge in pedestrian interactions. Since ABM allows a straightforward representation of any traffic entity, be it a pedestrian or an automobile, it is suitable for modelling traffic dynamics as well (see simulations of the car-following model by Hidas (2005)). According to Batty (2008), these models are less rooted in policy and practice and tend to be more speculative, dealing with intrinsic processes of change and how spatial structures might emerge out of it.

Multi-agent simulation vs ABM

Activity-based simulations are multi-agent, but not *truly* agent-based models. Agents in multi-agent simulations influence one another indirectly, through the congestion they generate, which results in costs to the household activity budget (Wise et al., 2017). However, there is no communication, coordination or purposive (joint) action between agents. The line between multi-agent simulations and ABM is blurry. While activity-based approaches represent a new paradigm for travel demand analysis as compared with trip-based approaches, the same cannot be said of ABM when compared with multi-agent models. According to Zhang and Levinson (2004), ABM is a powerful modelling tool to disentangle complex systems, but '*it is difficult and unnecessary to draw a line between agent-based travel demand models and activity-based approaches*.'

6.4 In summary

Recap

In this chapter, we have surveyed the methods in urban design that take into account transport flows, and the methods of prediction in transport planning and their relationship to urban form. Quantitative modelling in the mainstay of transport planning, and has remained so since the first transport models were constructed in the fifties. However, the methods of modelling have evolved considerably since then, in response to new planning challenges and policy thrusts.

From aggregate models to disaggregate models

When the early transport models were built, transport planning was grappling with the problem of accommodating the 'inevitable' growth in automobile traffic which required large scale interventions involving major public investment, making mathematical analytical techniques popular. Aggregate models were used to predict traffic flows and provide infrastructure for it. However, when it became evident that it would be impossible to accommodate the perpetually growth car traffic predicted by these models, the focus shifted to travel demand management. Modal shift from the private car to other modes began to be encouraged through policy in order to manage travel demand efficiently. The development of disaggregate models supported this by taking into account individual choices and preferences through discrete choice analysis.

From mobility based perspective to access

Both aggregate models and trip-based disaggregate models are based on the principle that mobility is the primary goal of transportation, but in the eighties and nineties, this view was challenged based on the assertion that travel is a derived demand. Travel is never an end in itself, but a means to access services and perform activities. Activity-based multi-agent simulation models, such as MATSim, support this view of travel. The availability of much more powerful computing capabilities at the time made such simulations feasible. The *truly* agent-based model further improved the resolution of these simulations by modelling the autonomous and social features of agents, enabling coordination and joint action. Agent-based models capture pedestrian and cyclist behaviour at a much higher level of detail than multi-agent simulation models.

Conclusion

The resolution of transport models has progressively sharpened over time, beginning with aggregated geographic zones, to buildings and individual behaviours, which allows a much better understanding of the effects of small scale urban design interventions on transport flows. However, within the discipline of urban design, transport flows are not represented and analysed at such a fine-grain scale. There is also no tangible link between transport models and conventional urban design methods. We will try to establish this link in the next chapter, with a proposal for a new methodological framework that challenges the dominant 'predict and provide' process we have today.

7 A Methodological Framework for Disciplinary Integration

In the previous chapter, we discussed the 'predict and provide' process as the dominant link between urban design and transport planning. This process ignores the strong two-way relationship between urban form and transport flows discussed in Chapter 5. The conventional methods in urban design also fail to adequately take into account transport flows, both in representation and analysis. In order to develop an informed response to the technological shift in transport, the purposive role of urban design to influence travel patterns must be supported, and a quantitative understanding of emergent transport flows must be included in the urban design process.

In this chapter, a methodological framework is proposed that integrates transport analysis and urban design in an iterative process. Multi-agent simulations are used for analysis since they allow a fine-grained spatial and temporal resolution of analysis that enables us to study cause-and-effect mechanisms for small scale design interventions. Exploratory modelling methods are used to integrate low-resolution urban design and transport models and analyse multiple design options through 'design experiments'.

7.1 The problem with ‘Predict and Provide’

Problems with predict and provide

Even as transport models became increasingly disaggregated and bottom-up in their approach, as discussed in section 6.3, their relationship to urban design is still predominantly defined by the ‘predict and provide’ process. This process is unidirectional, allowing no reciprocity between transport flow predictions and urban design which is especially problematic in the context of the technological shift in transportation. Predictions are increasingly unreliable and urban design methods alone are inadequate to cope with the new challenges of the technological shift.

Predictions rely on extrapolations, have quantitative bias

How technological shift will impact cities is uncertain and enmeshed in a complex web of interdependencies, as discussed in Chapter 3. As the unknowns rise, predictions are bound to be inaccurate (Childress et al., 2015). Prominent complexity theorist, Batty (2018), concurs that the notion that cities are complex systems is entirely resonant with the notion that ‘*we cannot predict the future.*’ Predictions tend to extrapolate past trends, which may be acceptable for short term planning but can be problematic for long term futures marked with rapid change and uncertainty (Bertolini et al., 2008; Pearman, 1988; Ratcliffe and Krawczyk, 2011). Predictions also have an inherent quantitative bias, focussing on measurable economic, demographic or environmental variables. In doing so, they underplay social, cultural and political variables and shift the focus to what *will* be rather than what *could* be (Cole, 2001; Shiftan et al., 2003). Design, on the other hand, is well-equipped to address questions regarding ‘what could be’, through synthesis (Kolko, 2010) and visioning (Shipley and Newkirk, 1998).

Urban design’s neglect of time and emergence

Methods in prediction have become more dynamic, from static aggregate models to the dynamic simulation models, but the same cannot be said for models in urban design which continue to neglect temporal aspects of transport flows (Cidell and Prytherch, 2015; Sevtsuk, 2014). Space and time are hardly ever addressed at the same time in urban design, which remains biased towards a spatial view. A two-dimensional plan is the preferred representation style in urban design reinforced by the rise of GIS-based analytical tools (Miller, 2007; Myers, 2001), which are much more developed than tools that support temporal analysis. An expanded toolkit for urban designers that addresses transport flow dynamics is crucial to address the challenges of the technological shift (Axelrod and Tesfatsion, 2006; Clarke, 2014; Perez et al., 2017)

Disciplinary apartheid

Integrating the two disciplines through a process that enables a feedback cycle between urban design and transport planning has been a challenging undertaking so far. Hillier (1996) believes that a 'disciplinary apartheid' exists between urban design and transport planning due to a 'form-function' gap. Those who analyse urban function cannot conceptualize design, while those who can conceptualize design, only intuit function. For example, the three physical roles of the urban street – as circulation route, as a public space and a frontage for buildings, are separately tackled by transportation engineers, urban planners and architect/ urban designer respectively (Marshall, 2004). There is also a scale gap between these disciplines, where transport planning begins with the regional scale and loses relevance at the local scale of decision making, and urban design begins with a group of buildings but hesitates to operate at the city level (Hillier, 1996). This disciplinary apartheid is detrimental to building a complete understanding of the city. An iterative urban design and transport simulation cycle is proposed to overcome this challenge.

7.2 Iterative urban design and transport simulations

Why disciplinary integration is key

Qualitative design methods are better equipped to handle uncertainty and social variables that are not easily quantifiable, but human intuition is limited, and a purely intuitive test could be inaccurate and biased. Quantitative methods in transport planning could enable a better analysis of dynamic processes in measurable terms but underplay non-measurable social, cultural and political variables. It is essential to connect the two disciplines in an iterative cycle, shown in Figure 7.1, that straddles the space between intuitive design and quantitative analysis. Instead of merely extrapolating from current conditions to predict future transport flows and provide infrastructure for it, this process allows us to analyse different design options to make informed design decisions.

Emergence and the iterative process

Using multi-agent simulations for transport analysis allows us to understand emergent effects, making it uniquely suited to address specific challenges of the technological shift in transportation. These models take an evolutionary view of the city, where bottom-up small scale processes evolve to produce an emergent order. Kropf (2009) observed that,

> *"There is a disparity between the fact that cities are the result of deliberate and coordinated human effort on the one hand and exhibit characteristics of 'self-organization' and emergent behaviour on the other."*

In the former view, urban designers shape the city to steer the future city into some sort of desirable state. In the latter view, they can only accommodate the emergent order, predicted through some sort of model. Can cities then be planned, or are they entirely emergent?

According to Batty and Marshall (2012),

> *"A city cannot be built out of a creator's imagination like a building, nor does it grow like an organism, steering towards an optimum."*

Difference in workflows

If cities are both planned and emergent, this view can be effectively articulated through an iterative process of urban design and simulation. Such an iterative cycle is hard to operationalise because of the differences in methods of operation in urban design and transport planning. Urban design tends to be prescriptive rather than predictive (Batty, 2017), even though it is grounded in reality and informed by predictions. Design workflows tend to be more intuitive and iterative than transport modelling. Amiel and Reeves (2008) illustrate the difference between these two processes, as shown in Figure 7.2. Reconciling these two ways of working in a multi-disciplinary team is a challenging endeavour.

Model as the point of integration

The 'model' in this case, can become a point of integration. Both transport planning and urban design rely heavily on modelling as a method of analysis and sense-making, respectively. While urban designers use physical or descriptive models, transport models are mathematical. If the two models can effectively communicate, an iterative design and simulation cycle can be enabled.

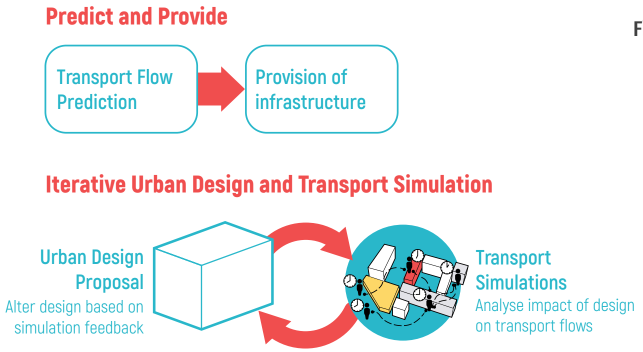
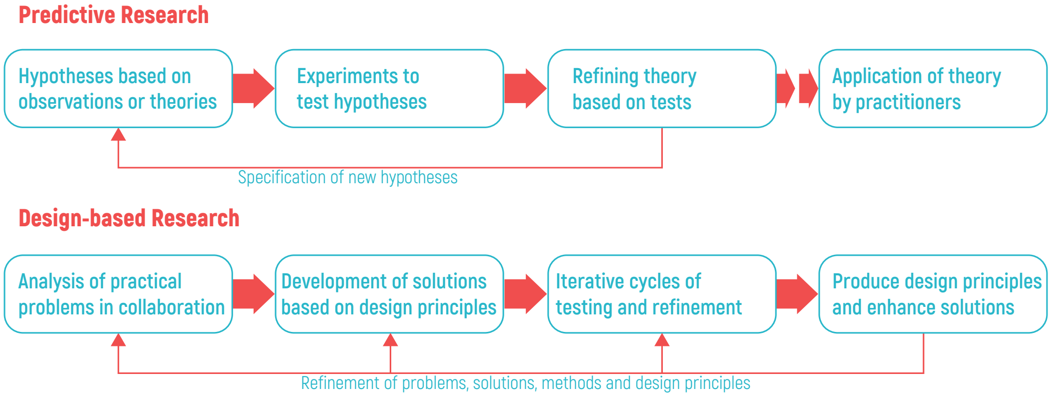


Figure 7.1 From 'Predict and Provide' to Iterative Urban Design and Transport Simulation

Figure 7.2 Predictive research vs design-based research
Source: Adapted from (Amiel and Reeves, 2008), Fig. 1, p 34



7.3 On models

What is a model

Often an artificial environment is constructed to test policies for new technologies and behaviours that do not exist in the real world (Allen, 2012; Ligtenberg et al., 2004). A model is nothing but simplified representation of some real-world condition under study. Both urban designers and transport planners frequently build models, albeit of different types. Architects and urban designer commonly use physical models for scale representations of design proposals. They also build descriptive models of functional and geometric aspects of designs proposals, such as 3D CAD models or GIS models. Transport planners use mathematical or analytical models, which replicate the system of interest and its behaviour through mathematical equations based on certain theoretical statements about it (Ortúzar and Willumsen, 2011).

Limitations of models

Physical and descriptive models in urban design are mostly static. They can be useful for certain types of transportation analyses, such as measuring accessibility using GIS (Sevtsuk and Kalvo, 2018), but they fail to capture complexity and emergence. At the same time, models in transportation have been criticised for their excessive complexity. In 1973, Lee famously wrote a requiem for large scale models (Lee, 1973). His criticisms included their overly large scope, much too coarse level of detail for actual policymaking, data-hungriness and high cost. Similar criticism has been repeated over the years by several scholars (Batty, 2008; Bertolini, 2017; Myers, 2001; Owens, 1995; Pearman, 1988).

Criticism for consolidative models

Models are not one to one representations of reality, but tools that allow us to study aspects of reality' (Portugali, 2012). This representation can neither be too abstract nor too detailed. A model should be designed specifically for the question under scrutiny, instead of attempting to represent the entire system. It is clear that Lee's criticism was not directed towards mathematical modelling as such, but towards what Bankes (1993) calls 'consolidative modelling'. Consolidative modelling is a standard approach in which known facts are consolidated into a single package and then used as a surrogate for the actual system. This approach often suffers from 'false reductionism' – the belief that the more detail a model contains, the more accurate it will be. No amount of detail can provide complete validation and as uncertainties grow, it gets even harder to arrive at a 'correct' prediction.

Models as a heuristic planning tool

In order to create a seamless interaction between urban design and transport planning, we need to move away from consolidative modelling, towards exploratory modelling. The urban design model need not to replicate the reality, but needs to represent a selective reality relevant to the research question. Similarly, the simulation model need not correctly predict future transport flows, but needs to indicate the probabilities of the city evolving in a specific direction, given a set of artificial conditions. Such a model can be considered a 'heuristic planning tool' (Portugali, 2012), a 'narrative' or 'storytelling tool' (Guhathakurta, 2002), a 'pedagogical tool' (Batty, 2008) in how it informs and extends our understanding, or a 'mediating tool' (Perez et al., 2017) accompanying knowledge building and sharing. Bankes (1993) describes such a process as 'exploratory modelling', which forms the basis of the methodological framework developed for this thesis.

7.4 Exploratory modelling and design experiments

Exploratory modelling for useful simplification

The proposal to integrate urban design and transport simulation models through design experiments rests on the notion of exploratory modelling as a theoretical foundation. According to Bankes (1993), exploratory modelling entails *'providing partial (or incomplete) information to the model in order to pursue partial answers'.* If large scale consolidative models oversimplify reality, replicating human decision-making behaviour purely through mathematical rules, exploratory models pursue 'useful simplifications'.

Example of hypothetical neighbourhood

Let us consider how such a useful simplification can be attained, through a simple example of a hypothetical neighbourhood with only three parameters: network connectivity, land use mix, and public transport provision. Each parameter has a plausible range of values from low to high, resulting in a virtual ensemble of models within this vast *'parameter space',* corresponding to the red solid in Figure 7.3. Every point within this parameter space is a plausible model. As the number of parameters increases, the number of models increases exponentially. Since it is not possible to run all plausible models, we need to carefully select a set of 'useful' models to run from this near-infinite ensemble. According to Bankes (1993), we must use heuristics to guide this search, by involving human decision-makers more interactively in the selection process.

Example of how to select

Through a heuristic search and stakeholder consultation, we can dramatically reduce the parameter space to a limited set of parameters of interest with a limited range of values. Let us say we are interested studying the interrelationship of three types of networks – gridiron, radial and suburban, three types of land uses – more residential, commercial or cultural, and a binary condition of public transport – whether it is present or not. Based on these values, we get a reduced parameter space, as shown in Figure 7.4, where we arrive at 18 unique models. For instance, the highlighted red cube represents a suburban residential area with no public transport.

Fewer but inaccurate models

Although we have dramatically reduced the parameter space, the models themselves are likely to be inaccurate and thus not useful, since they s are built based on partial information. According to Bankes and Lempert (2004), *"instead of constructing only one model as a mirror for the real world, an ensemble of alternative models allows us to look in many mirrors, each flawed in different ways"*. As long as the ensemble is sufficiently diverse given available knowledge, computational experiments can be performed by drawing examples from the ensembles of models to infer properties of the system.

Question driven design experiment

A set of models driven by a specific question of interest can be compared to obtain structural results regarding the comparative performance and trade-offs involved. Such a set of models is termed as a *Design Experiment* in this research. For example, if we want to study the impact of network topology on public transport accessibility in a residential neighbourhood, the associated design experiment has a set of three models, as represented by the red box in Figure 7.5.

Evolving genealogy of models

The questions of interest can only be identified through an iterative process that works in conjunction with model construction and simulation. According to Bankes (2002), as early experiments inform later ones, we can create an 'evolving genealogy of models'. Such human-mediated iterative experiments enable quantitative understanding of the cause and effect mechanisms and the trade-offs involved with different design strategies, in order to inform the final design synthesis. It must be noted that conclusions reached from such a limited set of design experiments may be refuted later by experiments not yet performed, as is common in physical experiments.

Three properties of exploratory models

There are three essential properties of exploratory modelling systems: agility, modularity and intelligibility. The need for quick testing of many scenarios repeatedly puts an upper limit on the time required to run the model (Batty, 2013; Grignard et al., 2018). Both Bankes (1993) and Marshall and Gong (2009) suggest reducing the model to the smallest resolution possible, to make them more agile, comprehensible and manageable. It should also be possible to change the resolution of the model in response to different questions asked during the analysis, thus displaying modularity and ease of reconfiguration (Batty, 2013). Finally, to make sound decisions based on model results, the cause and effect relationships should be clear (Batty, 2013; Cannon, 1973). The model should be intelligible, such that whatever the output, it is traceable to changes in input values. In the empirical part of this thesis, we will revisit these three properties for the modelling tools used in this research.

Figure 7.3 All Plausible Models within Parameter Space

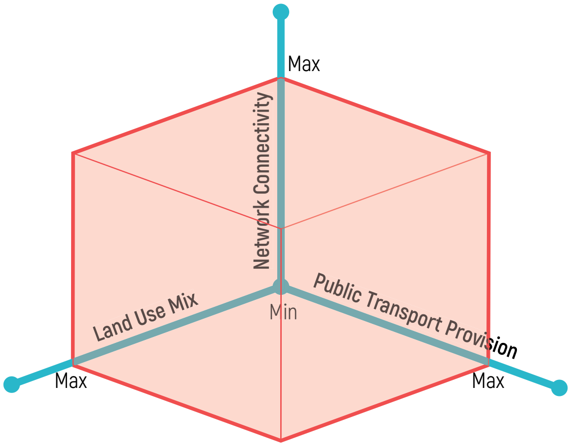


Figure 7.4 Reduced number of models with limited values for each parameter

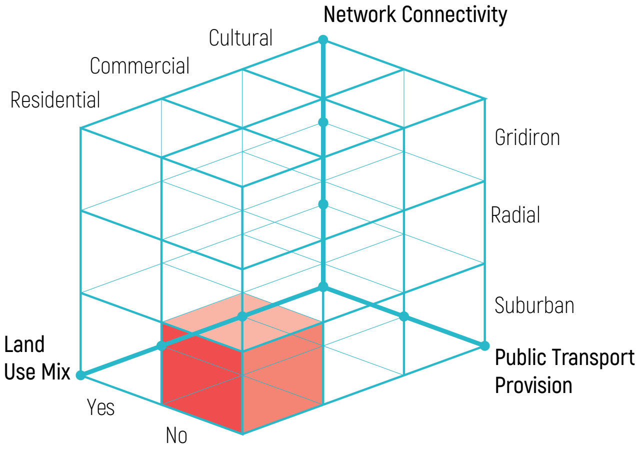
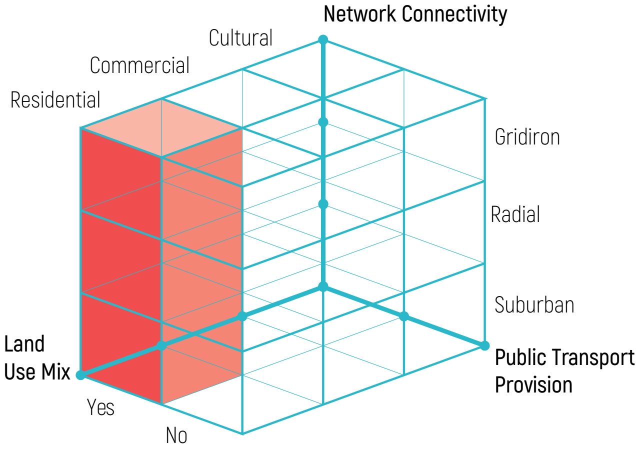


Figure 7.5 One Design Experiment



7.5 Proposed workflow

Disciplinary apartheid

Disciplinary integration between urban design and transport modelling has remained a critical challenge which is addressed here through an iterative urban design and simulation cycle that would replace the unidirectional predict and provide process (see Figure 7.6). The 'model' is identified as the point of integration, to establish seamless interaction between the urban design and the transport simulation. Since the empirical part of the research focusses on the neighbourhood scale, the spatial and temporal resolution offered by a multi-agent simulation is deemed sufficient to obtain useful conclusions.

Exploratory modelling and Design experiments

'Exploratory Modelling' is used as a theoretical foundation for the empirical work in this research. We begin with a large 'parameter space' with an infinite set of plausible models. The parameter space is reduced by identifying parameters of interest to create an ensemble of 'useful' models. We use heuristics to guide this search by involving human decision-makers more interactively in the selection process. From this ensemble, model sets are created driven by specific questions of interest, forming a 'design experiment'. Each design experiment can be modelled in a parametric design environment and evaluated through multi-agent simulations in an iterative cycle. Based on the results of the experiment, an appropriate urban design response can be constructed. This entire process is illustrated in Figure 7.7.

Quantitative bias

Both the construction and evaluation of the design proposal rely heavily on quantitative data in this proposed methodological framework, which can create a positivist bias. Two mechanisms have been employed to check this bias.

Collaboration

First, design experiments are constructed through a collaborative search for the question of relevance, such that the modelling procedure becomes more interactive and open. Many scholars have criticised esoteric transport models and advocated for a more collaborative planning process, where model results are not taken as a given but are used as a basis for debate and discussion (see (Grignard et al., 2018; Myers and Kitsuse, 2000; Perez et al., 2017; Wegener, 2013)). Design experiments provide a bridge between the pragmatic, contextual knowledge possessed tacitly by organisations, and quantitative data residing in the computer and mathematical framework (Bankes, 2002).

Avoiding collapsing evaluation into a single linear function

The second mechanism to check the quantitative bias is the provision of space for contestation at the evaluation stage. It is common practice to quantitatively evaluate the performance of a system based on several indicators and then collapse all of them into a single linear objective function, which is usually determined arbitrarily and exogenous to the problem (Batty, 2013). Such a linear objective function indicates the overall system performance but hides the cause and effect mechanisms behind it, effectively functioning as a black box. It is essential to leave space for contestation, maybe even without seeking consensus on the 'best-performing strategy' or 'preferred design solution'. The results from the design experiments are kept open-ended in this research and a path to a preferred future is charted through short, mid and long term scenarios. In the next section of this thesis, this proposed methodological framework will be operationalised through an empirical study.

Figure 7.6 Iterative urban design and transport simulations

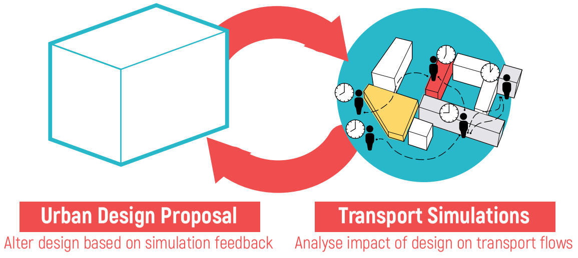
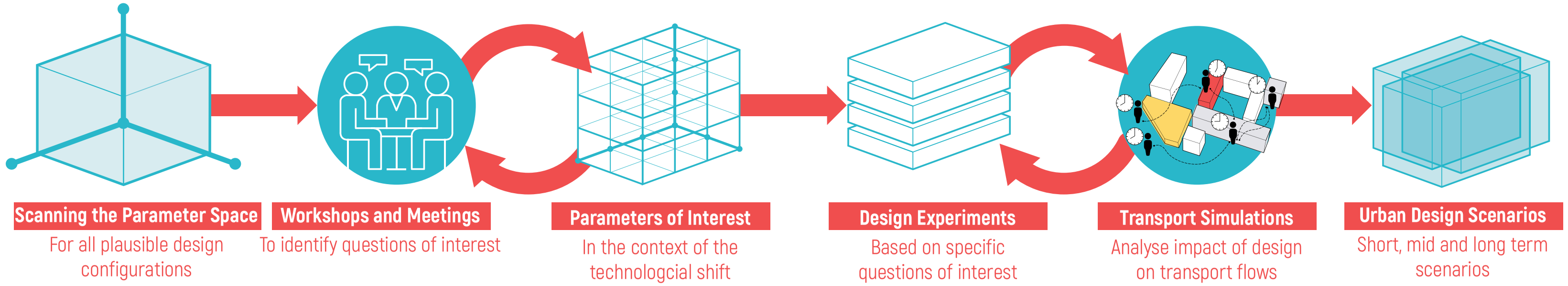


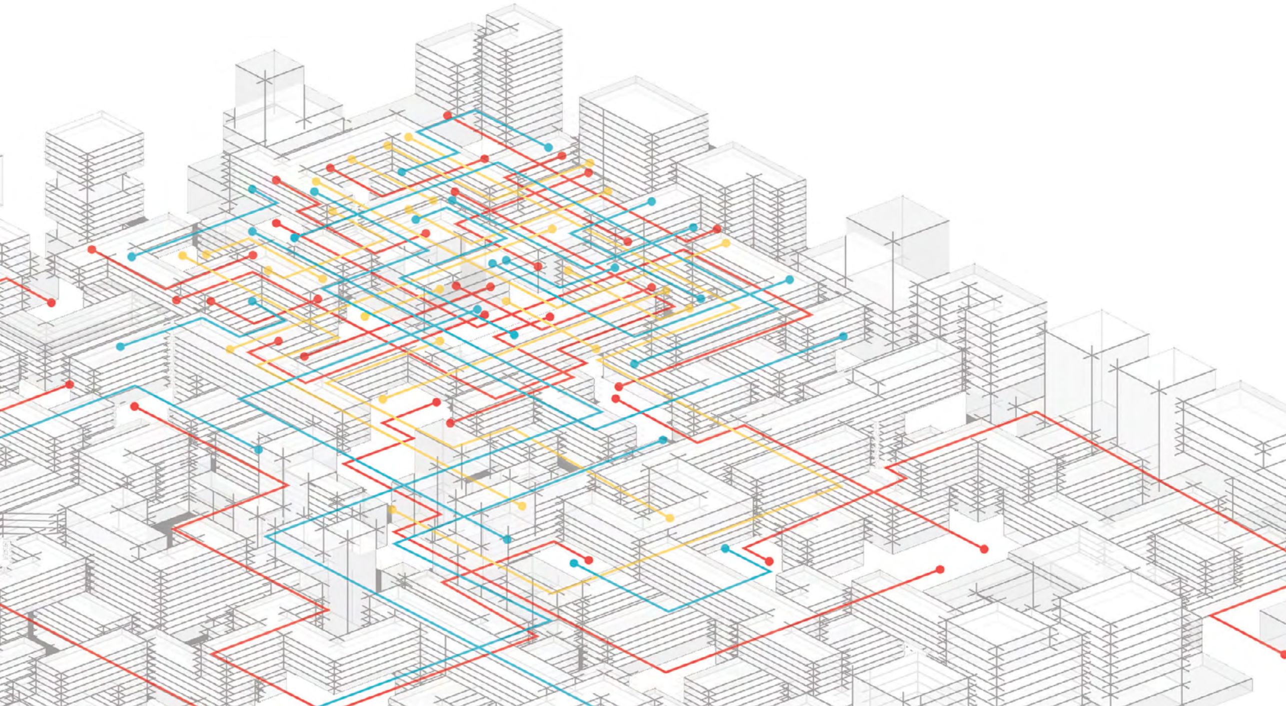
Figure 7.7 The workflow of the empirical study



PART 2

EMPIRICAL STUDY

The broader themes discussed thus far concerning the technological shift driven by vehicle automation, sharing, electrification, sensing and connectivity, and its impacts on the cities, will now be developed on a test site in a specific planning context. This study draws heavily on the inputs from the stakeholders involved in the L2NIC-AV project. The iterative design and simulation cycle was facilitated through Dr Pieter Fourie's considerable support with MATSim, and the extensive development work in Sketch MATSim and Spatial DRT accomplished by Dr Sergio Arturo Ordoñez Medina and Biyu Wang.



8 Modelling the Test Site

The context and site are essential elements of the methodological framework proposed in Chapter 7. We begin by setting out the rationale for selecting the site and the planning context – a typical Singapore Residential New Town where automated demand responsive transit or DRT was deployed – identified through stakeholder consultation enabled by the L2NIC-AV Project (see Appendix 1). Four questions of interest were identified, which later form the basis of the design experiments.

A detailed analysis of a typical Singapore New Town is conducted in order to construct an exploratory model with relevant parameters of interest in the context of this research. This model will be used to conduct design experiments at a later stage, to investigate how the prevailing New Town model can be modified (or reimagined) in response to the technological shift in transportation. The design and simulation models used and the link between them is described in detail in this chapter.

8.1 Reducing the parameter space

First step in the workflow

The first step in defining the experiments involved identifying the parameters of interest to reduce the initial parameter space, as shown in Figure 8.1. Parameters of interest encompass the various design issues, problems and their solutions that could be plausibly entertained given a combination of factors, including but not limited to, the aspirations of the stakeholders, the available data and the physical properties of the site and surrounding urban context.

The large initial parameter space

At the beginning of such processes, the parameter space is typically huge, where aspirations are as yet unchecked by other parameters, and needs to be simplified. In early technical meetings with L2NIC-AV project collaborators, for example, up to 15 possible scenario dimensions were identified, which included Road Pricing, Sharing, Network Constraints, Transport Mode, Charging, and Traffic Dynamics (see Figure 8.2). These dimensions alone result in a combinatorial explosion of 15 million plausible models. This large parameter space was reduced iteratively in collaboration with the stakeholder group.

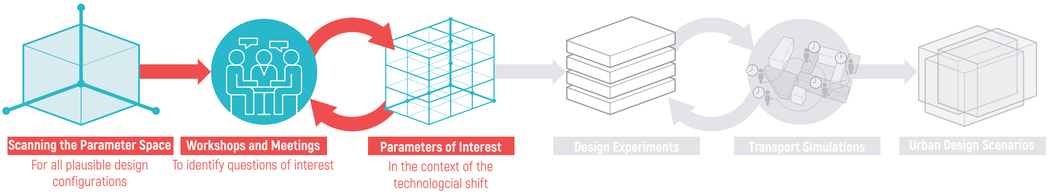
Two workshops

Two half-day workshops were conducted in 2017 with all stakeholders of the L2NIC project. The first workshop on 10 March 2017 was attended by 35 participants in Future Cities Laboratory, Singapore. It focussed on defining the scope of the investigation, including the operating model of shared automated vehicles and the urban context of operation. In the second workshop on 18 July 2017, design implications of the different operational models of AVs were discussed with 40 participants. These discussions contributed to the formulation of design experiments. For a detailed report the key conclusions of the two workshops, refer to Appendix 2.

Two decisions made in the workshops

Two primary implications of the workshops were the decisions made regarding mode and urban context of operation. There was general agreement on the design goal to promote a 'car-lite' future city, rather than an 'AV ready' city. Automated vehicles were expected to support existing public transport systems and not hinder active mobility. Consequently, a demand responsive transit (DRT) system was selected as the preferred operational mode. DRT is a form of shared public or quasi-public transport system where vehicles alter their routes based on transport demand rather than using a fixed route or timetable. Passengers can access these vehicles in a location of their choice, as a taxi, bus or any other type of vehicle.

Figure 8.1 Scanning the parameter space to identify parameters of interest



DRT would first be deployed in residential New Towns in Singapore, which currently houses about eighty per cent of the Singapore resident population (Cheong, 2016). New Towns are always served by at least one MRT (Mass Rapid Transit) station, and DRT is envisioned as a complement to the MRT, to improve the accessibility to transit hubs and serve as a first/last mile solution.

Set of assumptions

Once the mode and urban context of operation were decided, several other variables were fixed through a series of assumptions agreed upon over the course of the project. These assumptions ranged from demographic and environmental considerations to technological and operational ones, as summarised in Table 8.1. The process of building consensus on these assumptions, within the constraints of the L2NIC site and software technology, was long and contentious. There was general agreement on vehicle types, development density and priority for active mobility infrastructure, but some points of contention were identified where no decision could be made.

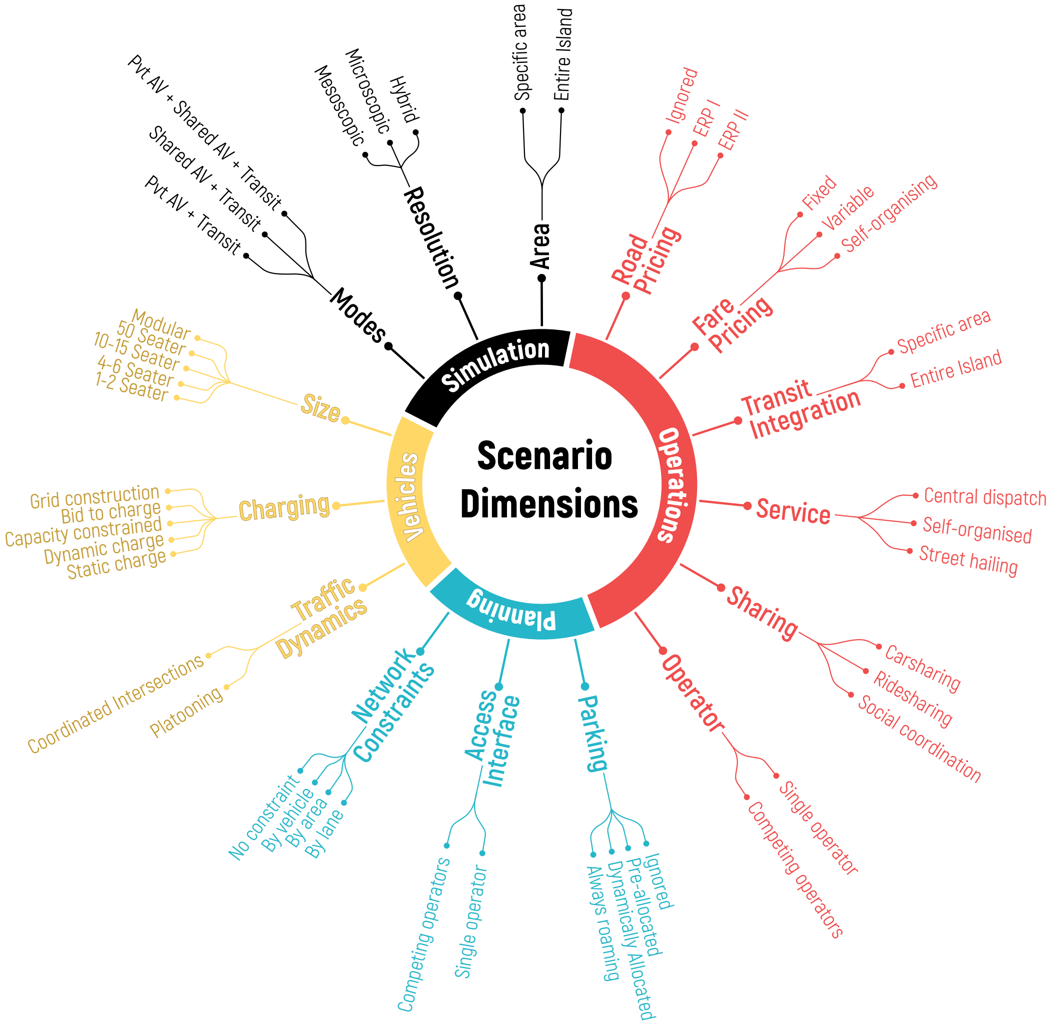


Figure 8.2 Possible parameters that could be tested
Source: Adapted from (Trinh et al., 2017)

Points of contention

Four points of contention that relate to urban design were – the design of street network, PUDO, parking and intersections. While some participants preferred complete physical separation between AVs and other traffic at intersections, others were sceptical about how it would affect walkability. There was also a lack of clarity around the optimal size and location of PUDO points and parking. For example, while some participants advocated building underground parking structures, it was difficult to determine its feasibility, when the total vehicle stock is unknown. The impact of network topology was also unclear, given different operating models, land use distribution and intended mode share. These points of conflict and uncertainty can be summarised in four questions of interest.

Table 8.1 Set of assumptions for building the models

Technology
Automated vehicles are safe to operate in a mixed environment with pedestrians and cyclists
High public acceptance of technology
On-demand transit is managed from a single dispatching system with complete information
Population
Demographic profile (based on a recently developed neighbourhood)
Future population growth (based on total buildable space)
Households’ vehicle ownership rate fixed based on a 0% vehicle growth rate for Singapore
Environmental Design
Future road and public transport network in the surrounding context fixed based on current plans
Average household and workspace size fixed based on current standards
Lane widths fixed based on current standards
Land use distribution (ratio of residential to non-residential area) fixed based on HDB standards
Vehicles and Operations
Vehicle operation area fixed for first and last-mile support only
Pricing model for ride-sharing and taxis fixed as a ratio of transit pricing based on(Bösch et al., 2018a)this research shows that public transportation (in its current form
Maximum detour factor for ride-sharing fixed
Maximum waiting time for MoD vehicle assignment fixed
Service levels of Fixed-route buses fixed
Based on software limitations
No change in micro-scale vehicle dynamics
No social coordination dynamics for ride-sharing
No surge pricing
No electric vehicle charging dynamics

How do we design the street network for new transportation systems?
Network topology can have strong effects on ride-sharing efficiency. A more connected topology may maximise pooled rides, but a more disconnected network is useful to minimise through traffic and reduce points of conflict. Other attributes of the street network such as maximum allowable speed or allowing only specific vehicle types on specific links, can also be effective strategies. While low-speed limits were generally favoured as a mechanism to create more walkable streets, it is unclear how it would impact the overall traffic flow, even with the efficiency gains of vehicle automation.

In the event of the end of private car ownership and total vehicle automation, how will we access transport options?
The design of pick-up/drop-off points (PUDO) is a crucial infrastructure requirement of the technological shift in transportation. Existing bus stops and taxi stands could evolve into PUDOs for DRT in the future, but the extent to which they need to be expanded to accommodate future demand would have to be determined. Additionally, the impact of PUDO locations on mode choice also needs to be considered. Would long walking distance to PUDOs reduce the attractiveness of shared vehicles and encourage more private taxi/car use? Or will fewer PUDOs enable more ride-sharing?

What will be the new requirements for parking infrastructure?
Given that all automated vehicles can park themselves, building remote parking lots located offsite or underground to accommodate shared vehicles were proposed. However, the feasibility of building such lots could not be determined since the parking requirement for shared vehicles is unknown. Additional vehicle kilometres generated by parking activity in remote lots also needs to be considered.

If AVs operate most efficiently when segregated from pedestrians, who gets priority on streets and intersections?
Automated vehicles have to be insulated from all non-automated actors on the street in order to maximise their efficiency. High speed segregated highways for automated vehicles were criticised for replicating the errors of modernist car-based planning. At the same time, the romanticised image of pedestrians, cyclists and AVs mingling together on a shared street were challenged given the current state of development of AV technology.

Four parameters of interest

The four questions indicate that we need to test four parameters through four different design experiments – network, PUDO, parking and intersections. Land use and density are other important parameters that would be highly valuable to include in future design experiments but are outside the scope of this research. Land use and density are assumed to be fixed based on strict pre-defined specifications in Singapore New Towns, provided by the Housing and Development Board (HDB). A parametric 'base' model was created that replicates the Singapore New Town in all its essential properties in the context of this research. The next section describes the history of the development of the Singapore New Town and what these 'essential properties' are that need to be replicated.

8.2 Singapore New Towns as the test site

Singapore as a model

The ‘Singapore urban model’ emerged in the early 1990s, at first as a Singaporean initiative, in a bid to ‘export’ its development model to China (Tianjin Eco-City, see (Ong Beng Lee, 2012)) and countries of Asia such as India (Ludher et al., 2018) and Vietnam (Curien, 2017). The city-state is lauded for two prominent planning successes – its housing overhaul to provide homeownership to 90% of the resident households (Cheong, 2016), and its progressive transport policies (Diao, 2018). However, the success of these policies in Singapore can not necessarily be seen as a model for replication.

Model that is not replicable, yet relevant

As an island city-state, Singapore is extremely space-constrained, while being run by a strong, single-tier government that can dramatically reform the cityscape. Barter (2008) holds the view that the sustainable transport policies in Singapore are not so by design, but by necessity given the demands of these unique conditions. Similarly, Singapore’s national public housing program is inextricably tied to its unique ideological, political, and economic practices (Chua, 2011). Despite this, Singapore has inspired piecemeal imitations of its planning policies elsewhere, such as road pricing in London and Stockholm, and implementation of Singapore-style high-rise housing estates in Asian cities with similar urban conditions and challenges. Given these successes, Singapore has been deemed a ‘model’ for urban development, that is relevant even if it is not replicable (Chua, 2011).

Singapore as a model for sustainable transport policies

Of particular interest here are the transport policies in Singapore, which have been lauded as a model for sustainable transportation by several scholars and commentators (Ang, 1993; Cervero, 1998; Newman and Kenworthy, 1999). High priority is given to traffic congestion avoidance to maintain its status as an attractive destination for trade and tourism (Yuen and Chor, 1998). One approach to achieve this is by controlling car ownership through competitive bidding to obtain a COE (Certificate of Entitlement). Another approach to discourage car use has been through road pricing which was first implemented in 1975, as a one-time zone-based license for purchase, and in 1998 as ERP (Electronic Road Pricing), following a pay-as-you-go principle, based on the prevailing average speed of the street (Diao, 2018). A third approach has been to provide good public transit alternatives such as MRT, LRT (Light Rail Transit), buses and taxis. The 200km MRT system serves over three million daily riders, while the 28km LRT system has over 200,000 daily rides (LTA, 2020). Over 70% of commuters go to work by public transit during morning peak hours, and the MRT plays a critical role in coping with this daily demand.

Future challenges for transportation in Singapore

Despite having curbed car ownership rates successfully (12 cars per 100 people) and maintaining high transit use, Singapore grapples with issues of land scarcity, accessibility to transit, active mobility, road safety and environmental sustainability. Today road infrastructure occupies 11% of the 640 square kilometres of total land area, compared to 13% for housing. Although all residential developments are served by MRT stations, first/last mile connection remains a point of concern (Shen et al., 2018). The emphasis on maintaining traffic speeds may also inadvertently result in hampering walkability and transit ridership, as well as pedestrian safety. Even though road deaths are low in Singapore by international standards, a high proportion of deaths are on account of vulnerable road users (VRU) (Barter, 2008). The greenhouse contribution of Singapore's high car use (per car) and the large taxi industry is also substantial, comparable to that of the passenger transport industry in European cities (Kenworthy et al., 2001).

How can technological shift tackle these challenges

In recent years, the technological shift in transportation has been seen as a possible solution to these challenges (Tan and Tham, 2014). Singapore is one of the pioneers in the development of AVs but follows a path very different from American or Euro-centric solutions. The focus is not on automation technology per se, but its integration in the existing public transit system. Shared automated vehicles could potentially supplement the MRT system as a first/last mile solution. The safety benefits of vehicle automation, space-saving benefits of shared automated vehicles, and reduction in emission promised by electro-mobility are all seen as potential means to tackle current transportation challenges.

Singapore's technological readiness

Singapore is well-positioned to develop a response to the technological shift in transportation as a high-density Asian city. Several AV pilots and trials have been launched since the formation of CARTS (Committee on Autonomous Road Transport for Singapore) in 2014. Notable among these are the trials in the technology campus of One-North, NuTonomy's AV taxi service, and full-size AV buses to be tested in Nanyang Technological University campus, in partnership with Volvo. According to a KPMG's Autonomous Vehicles Readiness Index (KPMG International, 2019), Singapore is 'the most AV-ready Asian nation'.

Singapore as a laboratory for experimentation

Singapore has often been seen as a laboratory for experimentation with policies and innovations. It is uniquely suited to implement new technologies, since the government can internalise many public benefits, through the increased value of government-owned property and government coordinated housing (Edelman, 2011). 80% of Singaporeans lives in such government coordinated housing or HDB estates. An Aspen Institute report (The Aspen Institute, 2017), called Singapore one of the world's '*most active laboratories for experimentation with automated vehicles*' in 2017, echoing the characterisation posed decades earlier by Liu Thai-Ker, former chief executive of HDB, who described the Singaporean New Town as an '*experiment in an urban laboratory*' (Liu et al., 1983). For these reasons, the New Town has been chosen as the site to operationalise this research.

8.2.1 The HDB experiment

The HDB Experiment

In the early years after independence, almost 35% of the population in Singapore lived in slums or squatters. To quickly provide high-quality housing to its population of 1.63 million, Singapore adopted a New Town planning model, primarily based on European post-war New Towns and Howard's Garden City (Eng, 1986; Lee and Park, 2018). New Town planning has evolved considerably since the first post-independence plans (see Figure 8.3) as new issues and challenges emerged, but some core principles persisted. The New Town in its essence remains a high rise, high-density self-contained development, demarcated by expressways, following a hierarchical structure of road system and facilities.

Stage 1

The evolution of New Towns can be described through four stages. In the initial stage (1960-70) immediately after independence, the focus was on alleviating the chronic housing shortage at a low cost. Queenstown was the first public housing developed between 1962-64, followed by Toa Payoh in 1966. Toa Payoh was the first residential development that explicitly dealt with decongestion through decentralisation (Lee, 2015), by creating a self-sufficient New Town on virgin land at the periphery of existing development. As shown in the image of the early construction phase of Toa Payoh in Figure 8.4.

Figure 8.3 Evolution of HDB New Towns

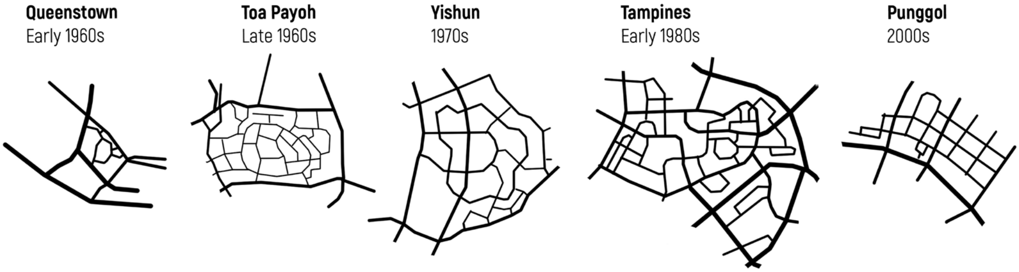


Figure 8.4 Beginning of construction in Toa Payoh in 1967
Source: (Heng, 2015)

Stage 2 By early 1970, when the immediate housing demand was met, the focus shifted towards the refinement of design and planning standards (Joo and Wong, 2008). The ideas of neighbourhood-based planning that germinated in Toa Payoh (Cheong, 2016), were systematically developed in Ang Mo Kio in 1973, based on a prototype model shown in Figure 8.5. Neighbourhoods were conceived as self-contained communities of about 6,000 dwelling units, sufficient to support a primary school, shopping and community activity nodes, within walking distance of 400 metres. The hierarchy of distribution of activity nodes was also more sharply defined. These centres were places 900 to 1,200 m apart so that they would not compete with each other. (Hee and Heng, 2004).

Stage 3 In the 1980s, with falling fertility rates and an observable scaling down of the housing program, more attention was paid to improve the 'sense of identity' of the New Towns, in terms of breaking away from their physical monotony and creating a sense of community. In the third stage (1980-90), the concept of 'Precinct' was introduced to foster this sense of identity. The neighbourhood unit was broken down into several smaller housing precincts of 400-800 dwelling units (Cheong, 2016). This number was derived from a British survey that showed that people could not relate to a residential area larger than 5-6 acre. This conclusion was supported by observations from local sociologists that 700-1000 dwelling units provide a suitable scale for a 'community' (Liu and Tuminez, 2015).

The chessboard model The first New Town 'Structural Models' were developed in the eighties, as a theoretical template embedded with design principles to guide planners in building HDB Estates. The structural model underwent several significant changes between the late seventies to the mid-nineties. The initial model followed a "chessboard" approach, as described by Liu Thai-Ker. Low-density shopping centres, schools, sports fields, and parks were interspersed with high-density residential to create an illusion of a low-density environment, as shown in Figure 8.6.

Structural model updated prototype The initial chessboard model gave way to an updated structural model, with a more clustered grid, distinct zones, and more hierarchy in zones and road network (see Figure 8.7). The initial service radius of facilities was reduced from 400-450m to 300m (Hee and Heng, 2004). The precinct formed the fundamental structural element, and considerable attention was paid to develop a unique architectural identity for each precinct. More landscaped greenery was also introduced as a buffer between towns, to create a visual identity and act as a community space for precincts (Cheong, 2016). Tampines was the first New Town based explicitly on this structural model, which is now the most prevalent model in HDB towns.

Stage 4 As Singapore became more vulnerable to environmental issues like loss of coastal land, increased energy demand, and public health threats, an emphasis on sustainable development was seen in New Town planning. The 'Estate Model' represents the fourth stage of development of New Town Planning, as shown in Figure 8.8. Punggol (1996–2011) was built based on this model and designated as Singapore's first 'Eco-Town'. Housing, education, shopping, and recreation were integrated into a compact, pedestrian-friendly, mixed-use developments served

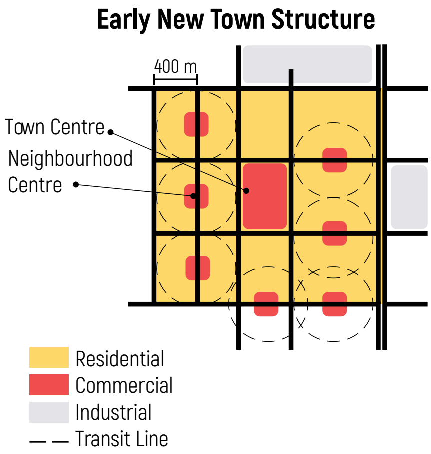

Early New Town Structure

Figure 8.5 An early prototype of New Town Structure
Source: Adapted from (Liu et al., 1983), Fig. 1, p 29

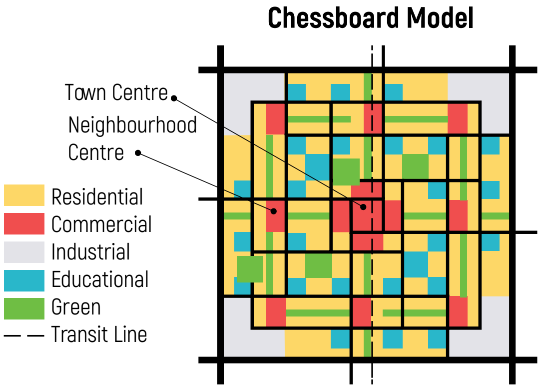

Chessboard Model

Figure 8.6 An early prototype of the HDB structural model
The 'chessboard' approach Source: Adapted from (Liu and Tuminez, 2015), Fig. 6.5, p 106

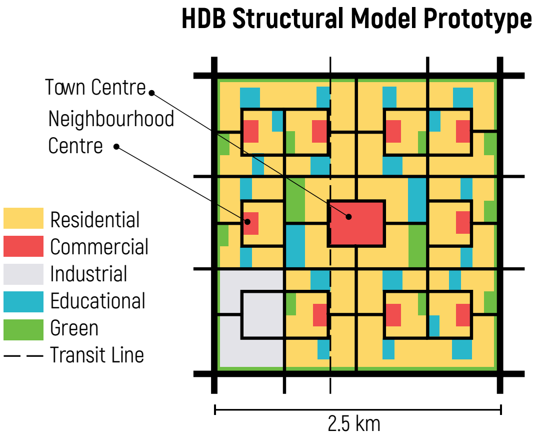

HDB Structural Model Prototype

Figure 8.7 Updated HDB Structural Model
Source: Adapted from (Cheong, 2016), Fig. 2, p 104

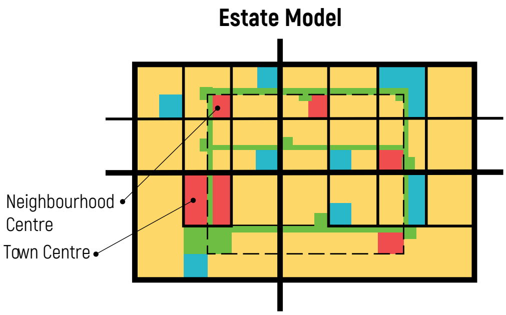

Estate Model

Figure 8.8 The Estate Model, implemented in Punggol
Source: Adapted from (Hee and Heng, 2004), Fig. 6.7, p 137

by transit nodes within walking distance of 300-350m. These principles are very similar to those advocated in Transit-Oriented Developments (TODs) and by proponents of the New Urbanist Movement (Hee and Heng, 2004).

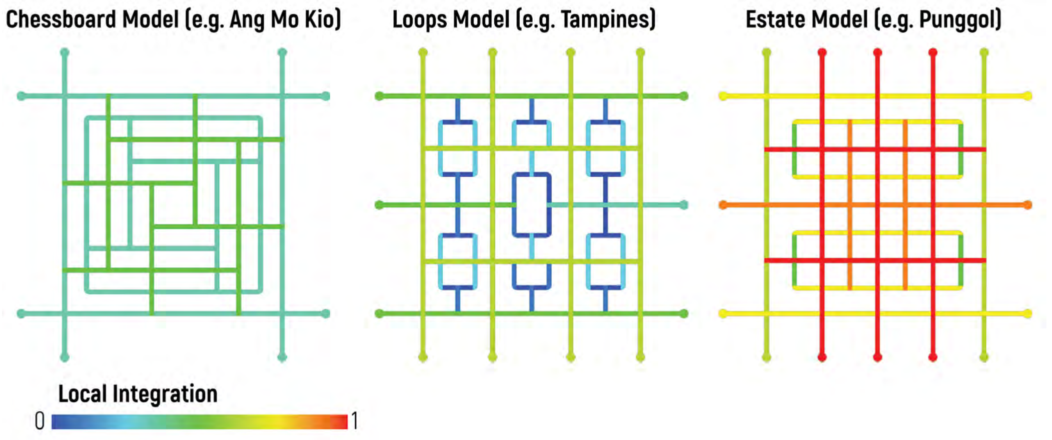
Evolution in model and goals

This evolution from the early chessboard model, to the hierarchical structural model implemented in Tampines, to the Punggol Eco-Town, represents the evolution in goals and aspirations of town planning in Singapore. Figure 8.9 shows how the network topology evolved in these models, first becoming more hierarchical, and then more connected in the Estate model. The blank-slate developments of New Towns have allowed planners to realise their theories free from more obvious operational constraints (Liu et al., 1983). How can the HDB New Town model evolve in the future in response to the technological shift in transportation?

Search for a new structural model

As HDB ramped up its housing program in 2010, it began a search for a model for a new generation of public housing, to support the increasing population while meeting the new urban challenges. Cheong Koon Hean, CEO of HDB, identified some key goals for this new model, such as developing a car-lite environment and achieving environmental, social and economic sustainability. This search for a new model must take into account the technological shift in transportation and leverage it to achieve these goals. This empirical study investigates how the prevailing New Town Structural model can be modified by drawing conclusions from the design experiments. In order to run these experiments, a parametric ‘base model’ was developed, representing some properties of the Singapore New Town in the context of this research question. The process of construction of this model is unpacked in the following section.

Figure 8.9 Street topology in HDB New Towns



8.3 Modelling the Singapore New Town

Fictional site over real-world site

A parametric model of a fictional Singapore New Town was built to operationalise this research, instead of selecting a real-world test site. Using a real-world site is useful to narrow the scope and search for implementable solutions. However, this can raise additional issues that are difficult to resolve. For example, even if the chosen site is undeveloped, it is usually located within a well-developed context, with existing flows and networks to be accommodated, compromising experimentation with the network design.

Burden of a real-world site

It was found that the ultimate burden of a real-world site was the pre-existing notions, aspirations and meanings that the collaborators inadvertently attach to it, which is especially problematic for projects exploring very long term futures. It is difficult for planners and policymakers to look beyond these constructed meanings and pragmatic short term concerns, to imagine a radically different long term future. This problem could effectively be overcome by using a fictional site.

The base model

The 'Base Model' was created in a way such that it mimics a Singapore New Town in only its essential properties that are relevant to the research question. The most widely implemented structural model in Singapore, best represented by T ampines, was used to develop the Base Model. ESRI CityEngine was used to construct the Base Model parametrically, and Sketch MATSim was used to analyse the transport flows through agent-based simulations. The fictional site was located on the Southern waterfront of Singapore and developed in five steps: the urban structure, density and land use, transportation system, parking and PUDO.

8.3.1 Developing the urban structure

The hierarchical structure of New Town

The New Town Structural Model follows a hierarchical pattern based on the repetition of a cell unit (Figure 8.10). Every Town is divided into 6-8 neighbourhoods, with 5000-7000 dwelling units. Each neighbourhood, in turn, comprises of 8-9 precincts, with 500-1000 dwelling units each (Joo and Wong, 2008). It is served by one 'Town Centre', usually located in its geographic centre, one neighbourhood centre for each neighbourhood and one precinct centre for each precinct.

Commercial centres and green spaces

The town, neighbourhood and precinct centres provide commercial and recreational facilities that hierarchically scale down. For example, a typical Town Centre has an integrated transit hub with MRT station and a bus terminal and large commercial development. A precinct centre has more local facilities such as child care centres and corner stores. Green spaces also follow a hierarchy but are more scattered in their organisation. In recent years, green corridors, known as park connectors, have been used as a device to network these scattered green spaces. Wherever possible, existing natural features are preserved.

Urban structure of the base model

The total site area of the Base Model is 531 hectares. The site comprises of six neighbourhoods, shown in blue outline, with approximately 6200 dwelling units each, served by three underground MRT stations on one line, located on its northern edge. (Figure 8.11). The Town centre is co-located with one MRT station, and each neighbourhood has one neighbourhood centre, shown in red, two of which are co-located with MRT stations. The town has hierarchically structured green spaces scattered through the neighbourhood. A large existing natural area is retained on the southern edge of the site.

Figure 8.10 New Town Cell Prototype

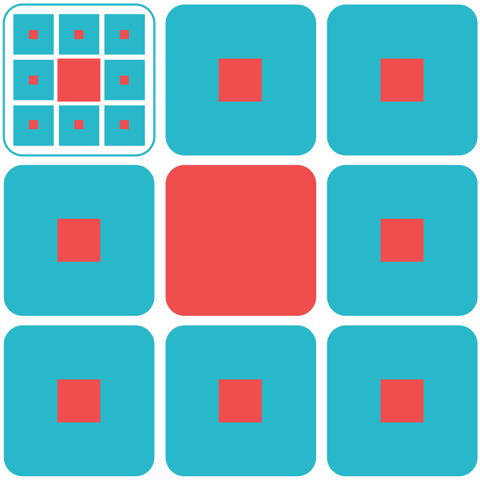


Figure 8.11 Urban Structure of the Base Model

8.3.2 Density and land Use

Density and land use in a typical new town

About 40% of the land area in a New Town Structural Model is allocated to residential development, and major roads occupy a significant amount of land, at over 12%. Table 8.2 shows the land use distribution in a typical New Town of 40,000 Dwelling Units. The land use is fairly mono-functional, with some provision for industry as job centres. The average net density in the residential area is 175 dwelling units per hectare, and the gross residential density is 60 dwelling units per hectare (Liu et al., 1983) which translates to medium to high-density development with an average plot ratio between 1.5-2.8. In recent years, space provision for industry has been scaled down, and higher plot ratios of up to 4 have been encouraged.

Density and land use in the base model

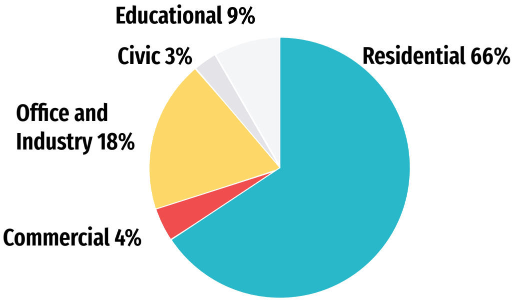
The Base Model was designed with a total of 37,307 dwelling units. The gross residential density is about 70 DU/hectare, and net density of approximately 150 DU/hectare, with a plot ratio of 2.8. Figure 8.12 shows the percentage distribution of built area by land use types in the Base Model and the built-up area by use in hectares. The spatial distribution of these land use is shown in Figure 8.13. For a more detailed description of land use distribution, the standards used in planning Tampines were used as a basis for the design, as shown in Table 8.3.

Figure 8.2 Land use in a typical New Town
Designed for 40,000 dwelling units. Source: (Liu et al., 1983), Table 4, p 41

Use	Hectare	%
Residential	270	40.9
Industry	130	19.7
Major Roads	80	12.1
School	65	9.8
Commercial (TC & NC)	30	4.5
Institution	25	3.8
Open Space	25	3.8
Sports Complex	20	3.0
Utilities	15	2.3
Total	**660**	**100.0**

TC: Town Centre; NC: Neighbourhood Centre

Figure 8.12 Land use distribution in the Base Model
As percentage distributions (left) and total area in Hectares (right)



Use	Area in Ha
Residential	399
Commercial	25
Office and Industry	112
Civic	17
Educational	52

Figure 8.13 Spatial distribution of land uses in the Base Model
Note: The colours correspond to the pie chart in Figure 8.12

Table 8.3 Planning Standards in Tampines
Source: (Foo, 2001), Table 3, p 36

Facilities	Standards
Shops	1 per 80-100 Dwelling Units
Primary School	2 per Neighbourhood
Secondary School	1 per Neighbourhood
College	1 per New Town

8.3.3 Transportation system

Transit and walkshed in New Towns

HDB towns follow the principles of transit-oriented development, with high density, mixed-use, hierarchical urban planning (Diao, 2018). An HDB New Town is always served by one or more MRT station, linked to a Town centre and a Bus terminal. Bus stops are usually located 200-300 m apart on the main arterial roads, and taxi pick-up/drop-off points on smaller internal roads. The neighbourhood centres are designed in a way that it is accessible by all residents in the neighbourhood within 300-400 metres pedestrian walkshed.

Road hierarchy in new towns

The street types follow a strong hierarchy, with wider high order roads located at the edge of the neighbourhood block, and narrower, slower access roads inside the block. There is a sharp contrast between the pedestrian experience on the internal and arterial roads (Figure 8.14). The arterials are designed with wide buffers between pedestrians and vehicular traffic, and overhead pedestrian bridges at crossings and mid-block bus stops. On the other hand, internal roads have little to no traffic. Although a large portion of pedestrian walkways pass through a car-free environment, it is not lined by any activity generating nodes (Lee and Park, 2018). Activity centres are instead designed as terminal nodes of pedestrian corridors.

Comparing network topology in base model with Tampines

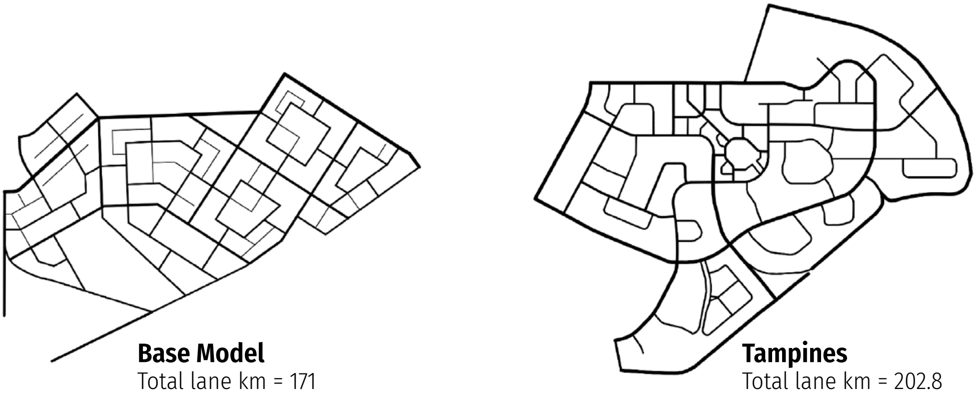
The road network is an integral part of the HDB structural model, giving it a strong geometric form. The Base Model is designed with a network topology resembling the Tampines structural model shown in Figure 8.7. Figure 8.15 shows a comparison between the network topology of Tampines and the Base Model. Since the size of Tampines is larger than the base model, the total lane km is higher, but the ratio of lane km to link km is similar in Base model and Tampines, at 3.68 and 3.94 respectively.

Street types in base model

There are six types of street profiles, the highest order lining the edges of the neighbourhood, and the lowest order serving as access lanes inside the precincts. The street profile description is given in Table 8.4, and their spatial distribution is shown in Figure 8.16. The north edge of the Town is served by a six-lane wide expressway, and each neighbourhood is bound by six-lane wide type 2 arterials. The secondary roads inside the neighbourhood are four lanes wide or two lanes wide. The service lanes are either narrow two-way type 5 or one-way type 6.

Figure 8.14 High traffic arterial roads (above) vs quieter internal roads (below)

Figure 8.15 Comparison of the network topology



Base Model
Total lane km = 171
Total link km = 46.4
Lane length/Link length = 3.68

Tampines
Total lane km = 202.8
Total link km = 51.5
Lane length/Link length = 3.94

Table 8.4 Street hierarchy used in the design experiment

Road Type	Street type	Total lanes	Sidewalk	Green buffer	Verge	Lane width	Median	Total Width	Max. Speed
1	Major Road – Dual Carriageway	6	2	2	3	3.4-3.7	4	39	90
2	Major Road – Two Way	6	1.5	2	1.9	3.4-3.7	0.6	32.4	70
3	Divided Two-way Primary Road	4	1.5	2	1.9	3.7	0.6	26.2	50
4	Undivided Two-way Secondary Road	2	1.5	2.5	0	5	0	20	30
5	Undivided Two-way Internal Road	2	1.5	1.5	0	3.7	0	13.4	20
6	Undivided One-way Internal Road	1	1.5	0	0	5	0	8	20

All units in metres. Speed in km/hr

Figure 8.16 Network design of the Base Model

8.3.4 Parking

In a typical HDB town, every precinct is provided with at least one multi-story or semi-basement parking structure, usually five decks high (Figure 8.17), in addition to some on-street parking. These parking structures are heavily underused during working hours on weekdays. Non-residents are not allowed to use these structures most of the time or allowed to use only the top two stories which can be inconvenient. The parking provision ranges between 0.4 – 0.8 spaces per dwelling unit. In the Base Model, every HDB precinct is provided with parking structures, and private parking is provided for condominiums. The total provision amounts to approximately 19000 parking spaces, with a provision ratio of 0.44 spaces per dwelling unit. Almost 77 hectares of built-up area is taken up by parking structures.

8.3.5 PUDO

According to HDB design norms, every precinct is provided with a maximum of two PUDOs or 16-24 PUDOs per neighbourhood. A PUDO consists of a shelter with some seating, and a bay size of 2.4 X 10.8 metres, as shown in Figure 8.18. The Base Model has a total of 161 PUDO points, of which 62 are shared with bus stops. Effectively, 18.5 PUDO points are provided per neighbourhood.

8.3.6 The complete base model

The complete model assembled

The Base Model is designed based on the principles embedded in the HDB structural model, and developed parametrically in CityEngine. The Base Model replicates a typical HDB New Town, in the essential properties that are relevant to the research question – urban structure, density, land use, transportation system, parking and PUDO, and assembled together as shown in Figure 8.19. Such a parametric model can be quickly modified to test several design options iteratively in a design experiment. These parametric layers can also later be integrated with a multi-agent simulation framework, as shapefiles.

Layers required for simulation

Seven layers of information are required for the simulation in MATSim, as shown in Figure 8.20. The three essential layers are road network with road type information, buildings with use type information, and transit lines with schedule information. Additionally, since we are interested in understanding the parking and PUDO dynamics for automated shared vehicles, we also require a parking facilities layer and a PUDO location layer, both with capacities. Two additional layers were created for further analysis: a pedestrian network layer with information on specific pedestrian infrastructure features, and a node layer with intersection type information. In the next section, we will discuss the simulation model in detail.

Figure 8.17 A typical parking structure in a New Town

Figure 8.18 Dedicated Pick-up/Drop-off point in a precinct.

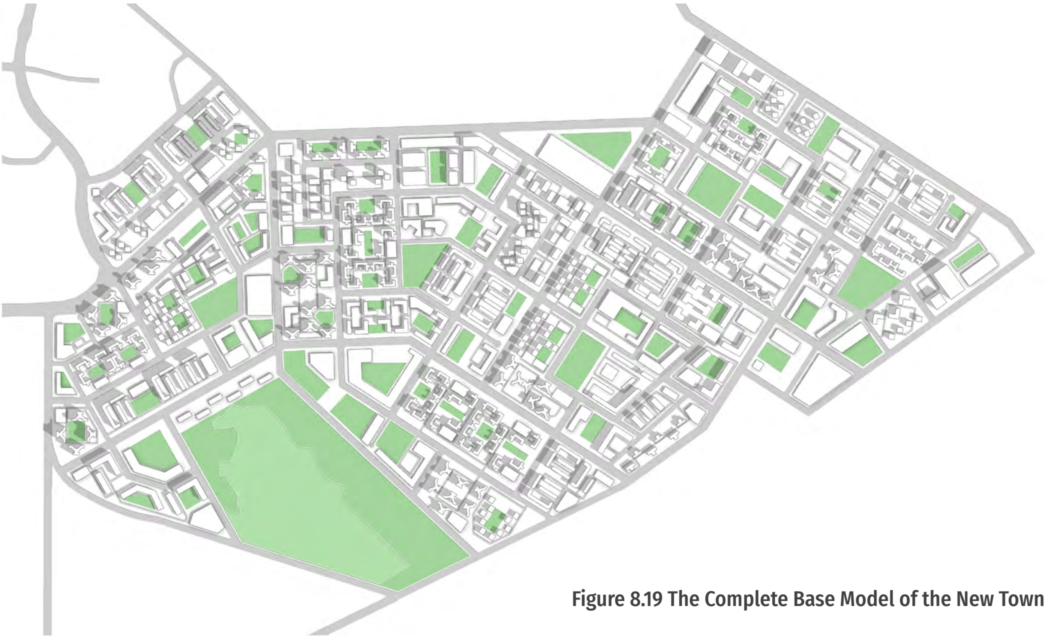
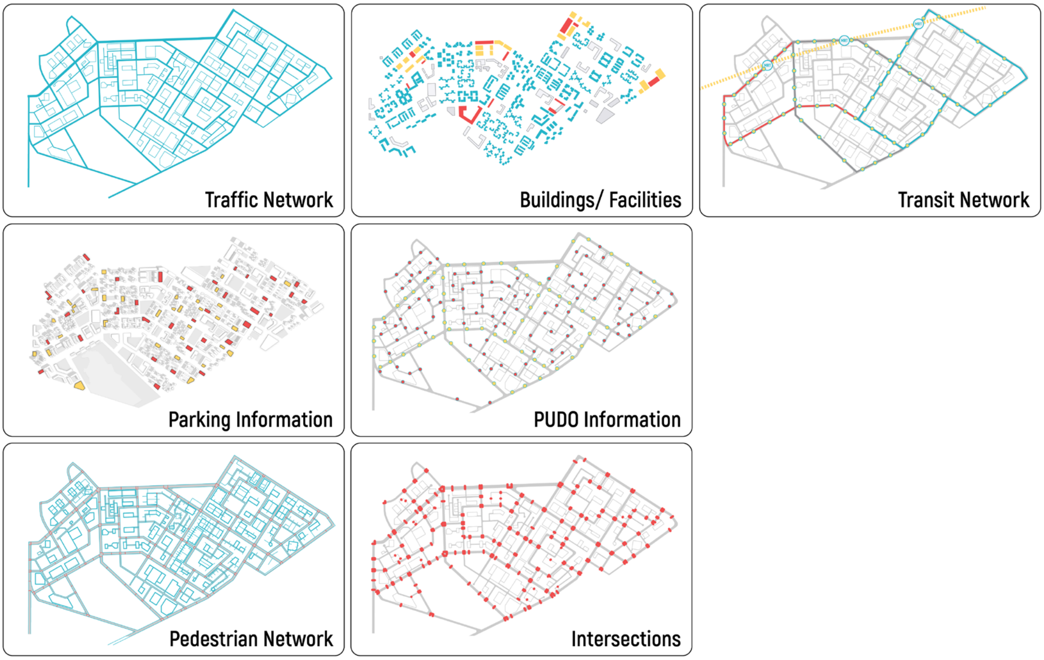


Figure 8.19 The Complete Base Model of the New Town

Figure 8.20 The seven layers of the parametric base model



Traffic Network

Buildings/ Facilities

Transit Network

Parking Information

PUDO Information

Pedestrian Network

Intersections

8.4 Simulation model in MATSim

Performance cannot be analysed intuitively

Once the design model is constructed, the different design options need to be assessed. In urban design, it is common to evaluate design solutions intuitively, but such intuitive assessments are likely to be biased and inaccurate. For example, when Dill (2006) compared a new urbanist neighbourhood with two conventional ones in Oregon, she found that while residents were walking more in the former, they may not be driving less as a direct result of the New Urbanist design features. It is judicious to not rely on intuition alone when testing design conjectures, especially in the context of the technological shift in transportation and growing urban complexity (Cannon, 1973; Clarke, 2014; Karimi, 2012)

Shortcomings of using GIS

In this research, agent-based simulations are used to assess different design options in the design experiments. Of all analytical methods in urban design, GIS remains one of the most widely used, partly because of disciplinary association with geography. Although GIS effectively links the functional and formal aspects of design to provide useful analyses, it can be limited in its representation of functional relationships based on flows systems, such as traffic movement (Batty et al., 1998). MATSim (Multi-Agent Transport Simulation) is used for design analysis here, which combines a physicist's and a civil engineer's perspective, bringing together expertise in traffic flow, large-scale computation, choice modelling and Complex Adaptive Systems (Horni et al., 2016). MATSim is particularly useful for this analysis since it is an activity-based, extendable, multi-agent simulation framework, which allows different design configurations to be simulated in an exploratory modelling framework.

MATSim Introduction

Simulations in MATSim are based on a co-evolutionary principle, where different species co-evolve subject to interaction (e.g., competition). We first start with an initial demand, as shown in Figure 8.21, arising from the study area's population and activity locations, developed from the input layers shown in Figure 8.20. The modelled persons are called *agents*, and their *activity chains* are usually derived from some sort of empirical data or discrete choice model. Every agent possesses a memory containing a fixed number of day plans, and each plan consists of a daily activity chain. Each plan is associated with a *score*, which is nothing but an econometric utility of the plan. The actual performance of agents is evaluated in a scoring step after a full day simulation, or the *first iteration*, is run in mobility simulation (mobsim), as shown in Figure 8.21. The agents are rewarded for performing activities and penalised for travelling and arriving late at activities.

Replanning and analyses

Initially, all agents tend to take the same routes to their destinations and travel more or less at the same time, resulting in massive congestion. To overcome this, they perform a mutation. After every iteration, a certain number of agents modify their plan (replanning). Four dimensions are usually considered for replanning: departure time (and, implicitly, activity duration), route, mode and secondary activity location. The agents can adapt plans based on random mutations, best response choices or approximate suggestions. For example, routing often is a best-response modification, while time and mode replanning are random mutations. The iterative process is repeated until the average population score stabilizes (represented by the loop in Figure 8.21), after which the system performance can be analysed at the desired resolution. This simulation framework exhibits the three properties of exploratory models.

Intelligibility

MATSim is firmly based on events stemming from mobsim. Every action in the simulation generates an event, which is recorded for analysis. These event records can be aggregated to evaluate the simulation at the desired resolution allowing analysis of cause and effect mechanisms in greater detail. However, as the information in the model grows, it may get harder to relate an effect to a specific causal mechanism.

Modularity

MATSim is an open-source software platform that is highly customisable. It greatly benefits from the development efforts of other researchers and practitioners in the domain. Figure 8.22 shows various modular elements that could be combined with MATSim at different stages. In recent years, several new modules have been developed in response to the technological shift in transportation, one of which, DRT (Demand Responsive Transit), is used in this research and discussed in greater detail in the next section.

Agility

The queue-based approach of MATSim

Since MATSim is designed for large-scale scenarios, it adopts the computationally efficient and simplified queue-based approach (QSim) to simulate vehicle movements. QSim is much quicker than detailed modelling of vehicle movement found in other truly agent-based microsimulation approaches discussed before. In the queue based approach, a car entering a road segment from an intersection is added to the tail of the waiting queue. It remains there until the time for travelling the link at free speed has passed, and the vehicle reaches the head of the waiting queue, and the next link allows entering.

Not enough agility despite queue-based approach

This approach is very efficient but comes at the price of reduced resolution. Furthermore, as the scale and complexity increases, the runtimes can still be much longer than needed for exploratory modelling, especially so with more computationally expensive modules such as DRT Extension, discussed in the next section. This shortcoming is addressed through the development of ‘Sketch MATSim’, a much more agile, albeit a coarser version of MATSim, discussed in section 8.4.2.

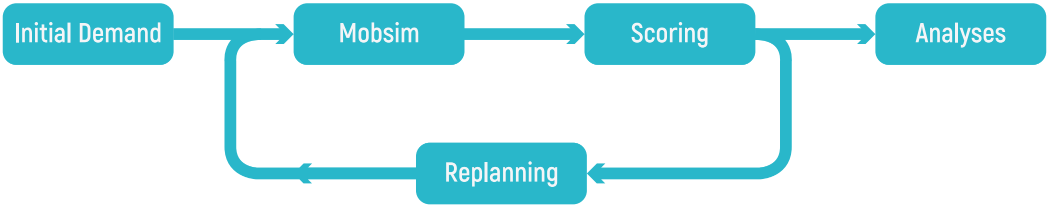
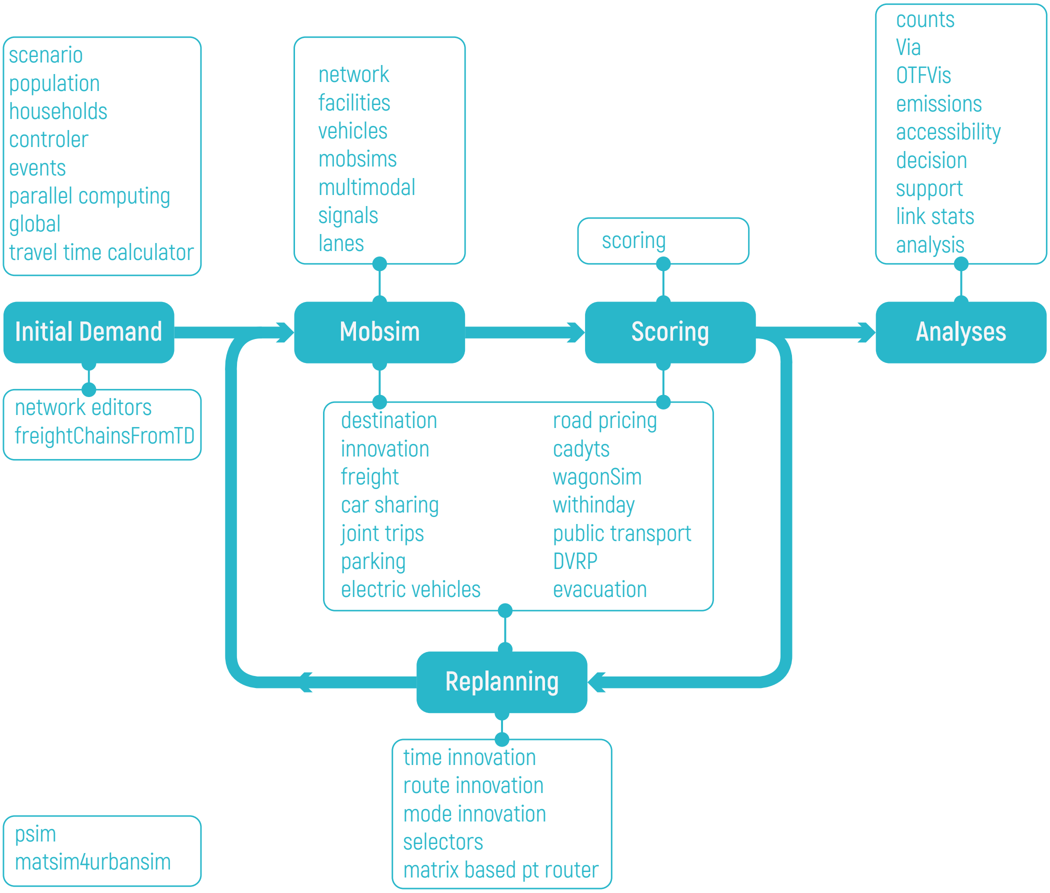


Figure 8.21 The MATSim Loop

Figure 8.22 Customising MATSim
Source: Adapted from (Horni and Nagel, 2016), Fig. 5.1, p 50



8.4.1 DRT Extension

DVRP extension

A critical component of the technological shift in transport is vehicle sharing and mobility on demand. Since access time to service is a fundamental parameter in mode choice, a high spatial and temporal resolution is required for simulating mobility on demand. An agent-based simulation approach is most suitable for this purpose (Ciari et al., 2009; Navidi, 2019). The DVRP (dynamic vehicle routing problem) extension of MATSim (Maciejewski, 2016), contains a framework for scheduling vehicles according to tasks. Depending on their schedule, these agents may pick up or drop off passengers or goods, like a taxi service. While DVRP and taxi extensions are only able to serve a single request per vehicle at a time (equivalent to a regular taxi use), the DRT extension (Bischoff et al., 2016) allows several passengers on board at the same time (see Figure 8.23).

DRT Extension

The MATSim DRT extension captures the behaviour of a transit system that is not bound to routes and schedules, which is useful to simulate automated transit with dynamic routing and ride-sharing. When a passenger sends a new request to the dispatcher, it evaluates the existing fleet and selects and assigns the vehicle best suited to make a pickup while maintaining a realistic level of service by allowing ‘reasonable’ detours. Reasonable detours are defined by a maximum waiting time constraint for new passengers and maximum in-vehicle travel time detour factor for passengers to be dropped off. These conditions only apply to request dispatching, and sometimes passengers may wait longer than the maximum waiting time due to unpredictable traffic situations, such as congestion.

Spatial-DRT Extension

As a part of L2NIC-AV project, Ordoñez Medina et al. (2018) developed the Spatial-DRT extension (shown in blue in Figure 8.24) to include finer-grained spatial elements like parking and pick-up drop-off (PUDO) points. This extension includes different parking strategies such as demand-based cruising and parking on the street, as well as different bay infrastructure for PUDO activity. When there is sufficient bay space, a vehicle is permitted to dwell immediately. If the bay capacity is insufficient, vehicles start queuing up, reducing the flow capacity of the corresponding link. These strategies are linked to the questions developed for the design experiments in this research. Similarly, new modules can be implemented, in response to other design questions, such as comparing different intersection design options.

Figure 8.23 The implementation of DVRP and DRT Extension in MATSim

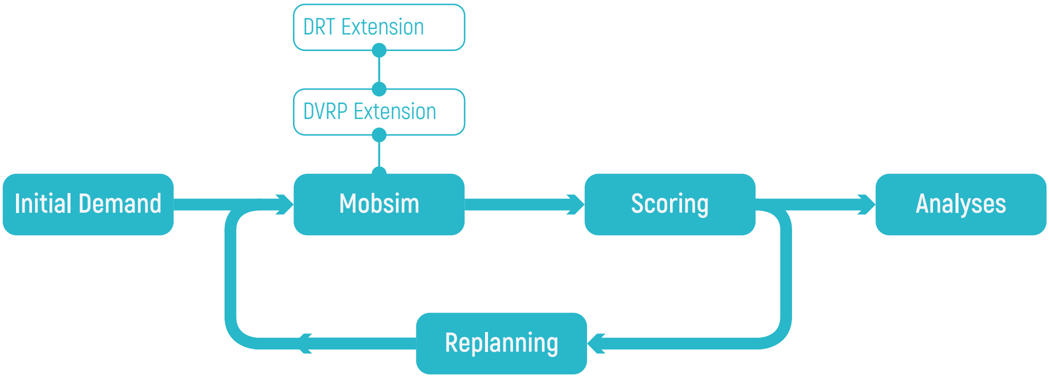
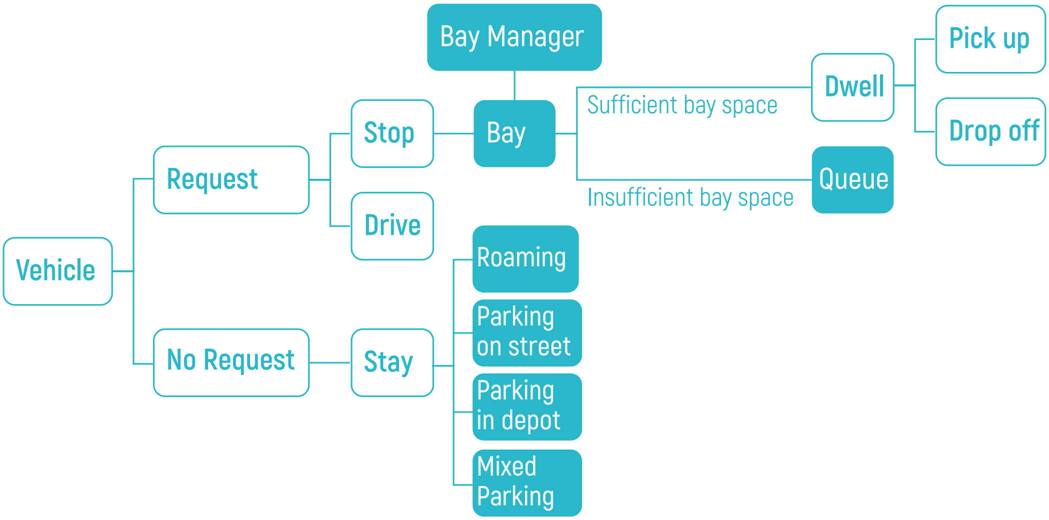


Figure 8.24 Implementation of Spatial DRT
Spatial DRT implementation shown in blue and DRT in white.
Source: Adapted from (Ordoñez Medina et al., 2018), Fig. 1, p 6



8.4.2 Sketch MATSim

Reduced computation time in Sketch MATSim

Long simulation runtimes of modules such as DRT, and the reduced granularity of information, is problematic when several design options need to be tested quickly. Sketch MATSim was developed to address this issue. Commonly, an entire urban system (for example, the whole city) is modelled and simulated in MATSim. In the context of the research question, the area of interest is limited to a neighbourhood scale. The site information is maintained in high resolution, while the global condition is abstracted out. A fixed number of incoming and outgoing daily trips and activity chains are assumed for the neighbourhood. Design layers shown in Figure 8.20 are imported in Sketch MATSim as shapefiles through a user interface, as shown in Figure 8.25.

Data requirements for Sketch MATSim

The simulation run times are considerably reduced when using Sketch MATSim. For example, a single iteration of simulation for the entire island of Singapore can take hours, and even more so with DRT. In Sketch MATSim on an average, every iteration takes about 7 minutes. This difference becomes significant once the total number of iterations amount to 100, which is required to reach a stable score for all travel plans in the simulation. The more iterations we run, the more stable the results. We find 100 iterations as a good number to achieve a stable state to conduct useful analysis.

Limitations of Sketch MATSim

In Sketch MATSim, we trade-off accuracy with runtime allowing us to test several design options quickly. Global events impact local processes and vice versa, and this information is also entirely left out of the model when we aggregate all incoming and outgoing trips. Such 'partial' models are useful in exposing structural variations across the model ensembles and intuit the underlying cause and effect mechanisms.

8.4.3 Demand generation in Sketch MATSim

Generating initial demand

Once an environment is generated for agents to interact in the simulation, we need to generate transport flows, or trip patterns, for the agents, which constitutes the initial demand, as shown in Figure 8.26. The travel demand could be as simple as a direct translation of census data, or could be generated using more sophisticated methods based on multiple big data sources. In Sketch MATSim, initial demand is generated from the spatial information provided by the layers of the base model, following a particular data-driven approach. This approach is similar to the traditional industry-standard methods used in a four-step model but relies on machine learning to pick up on non-linear interactions that cannot be captured in a rule-based linear model.

Data-driven approach to demand generation

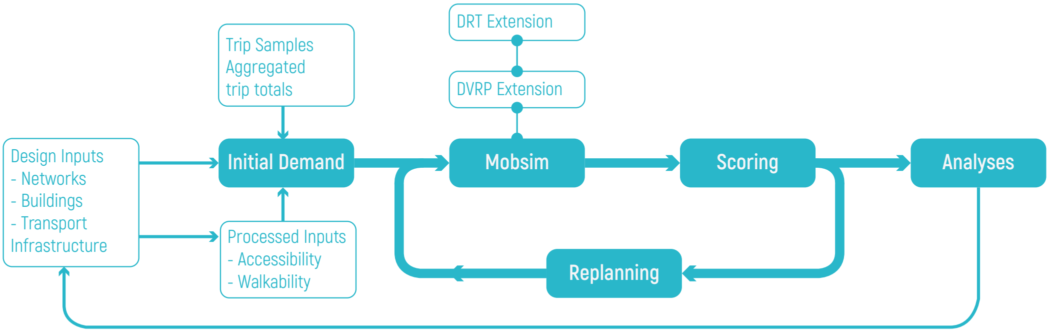
Typically, we take travel survey data as a source of rich information about when trips are being produced and attracted to known buildings with known space allocations, and some aggregate source of travel demand as a control total, such as hourly OD matrices produced from cellular phone data. These inputs are fed into a machine learning process that tries to generalize from the observed visitation patterns and building attributes, when and how many people will be attracted to buildings of various types during the course of a day. The machine learning process produces travel demand and trip patterns across the neighbourhood of interest. For more information in this data-driven demand generation process, refer to (Fourie et al., 2020).

Iterative design-simulation process

This initial demand is used as an input in the simulation. After every iteration, the travel plans are scored and modified based on the score for the next iteration. After 100 iterations, when the overall score starts to stabilise, we analyse the simulation results from the last iteration, as shown in Figure 8.26. This analysis then feeds back into the original base model design.

Figure 8.25 User Interface for Sketch MATSim

Figure 8.26 Demand generation in Sketch MATSim
Source: Adapted from (Fourie et al., 2020), Fig. 6.3, p 183



8.4.4 Vehicle population

Once the environment and initial demand are generated, we need to input the stock and service of all available transport options in the simulations. In our experiments we are working with six modes of transport:

Private cars

Singapore private car stock

In 2018 Singapore had a total car population of 618,055 vehicles, including privately owned and rental cars (Department of Statistics, Singapore, 2019). Singapore instituted the Certificate of Entitlement (COE) system in May 1990, to control the growth of the vehicle population. The annual vehicle growth rate is carefully monitored and moderated through this system. From 2008, this growth rate had steadily been reduced from 3% to 0% in 2017. Thus the overall vehicle population is not expected to increase from the figure in 2018.

Private car stock in the base model

Through discussions with collaborators from HDB, it was decided to provide 0.44 parking spaces per dwelling unit. Thus in the base model, we can assume private car population of about 16,415 cars, based on the provision of 37,307 dwelling units. All 16,415 cars in the model are automated and connected. In the simulation, our goal is to nudge these private vehicle owners towards other shared transport modes.

Taxis

Base Model Taxi stock

In 2018, Singapore had 2,581 taxis, which amounts to 3.65 taxis per 1000 persons. Given the population of the base model, 500 taxis have been provided to serve the neighbourhood. In the model, the taxis are one-seater and only serve door to door trips. All taxis are connected and automated and operated by a single operator.

Base Model Taxi pricing

In Singapore, taxis can be 600-700% more expensive than buses. However, with vehicle automation and electrification, the cost of taxi service is expected to go down. Bösch et al. (2018a) did a cost-based analysis of automated mobility service in for Zurich and found that automated taxis will be only 70% more expensive than automated buses, as compared to 415% before automation. In this model, private taxi service is priced 70% higher than public transit fares.

DRT

DRT concept and pricing

Demand responsive transit, DRT, is a hybrid between a taxi and a fixed-route bus, in that they are large size shared vehicles like a bus, but do not follow a fixed-route. DRT vehicles serve as a first/last mile solution within site. They are available on-demand through an online platform based service, managed by a single dispatcher (no competing services), similar to a shared ride or ride pooling service offered by some ride-hailing platforms today, such as UberPool or GrabShare. In the cost model of automated mobility service developed by Bösch et al. (2018a) automated pooled taxis were found to be 21% more expensive for an individual than automated buses. The same pricing has been implemented in the base model.

Detour factor and waiting time

In the experiments, DRT vehicles are allowed to make a detour of up to two times the direct distance to the destination if there was no ride-pooling. When a user requests a DRT, the router searches for vehicles within 7 minutes' travel time from the user (this is pre-calculated based on link travel time in the previous iteration).

If no vehicle can reach the user within 7 minutes, the DRT request is considered 'rejected'. Eventually, the user may have to wait longer than 7 minutes due to congestion. Rejection rates can be very high if there is a high level of congestion or low provision of vehicles. The number and size of DRT vehicles provided in the simulation is a critical input.

Size and stock of DRT

DRT vehicles could be any size, but a bigger vehicle size is preferred to maximise ride-sharing. In the base model, we provide 360 vehicles that can carry 20 passengers. Since the site is rather small (not larger than 3.3 km across), the DRT trips are expected to be short. Thus the vehicles can carry both standing and seated passengers. An example of such a shared automated shuttle is proposed by the research team at TUM CREATE, through the design of DART (Dynamic Autonomous Road Transit) modules. These vehicles are roughly 6 X 2.6 meters in size and can accommodate up to 12 seated passengers, as shown in Figure 8.27. The dwelling space required for PUDO activity of such a vehicle is assumed to be 8 meters in the experiments.

Scheduled bus and MRT service

In addition to DRT, the site is also served by regular scheduled automated bus service and a Mass Rapid Transit (MRT) line, routed as shown in Figure 8.28. Fifty seater buses ply on three circle lines, in both clockwise and anti-clockwise directions. The dwell length required for these automated buses is 13 metres. The buses arrive every seven minutes all day, and every 3.5 minutes in peak hours. The site is served by three MRT stations, as shown in Figure 8.28, all on one line. The frequency of the trains is five minutes in off-peak time and 2.5 minutes during peak.

Walking

Beeline distance factor

Walking is the final transport mode available to users on site. In Singapore, a walkshed is considered to be 300-400 m walking distance from the destination. In the simulation, walking distance is calculated through something called the 'beeline distance factor' which is a factor multiplied by the direct crow's flight distance between two points, to generate total walking distance. The beeline distance factor can vary greatly depending on the pedestrian network design. Considering Singapore's somewhat disconnected 'Loops' network, a beeline distance factor of 1.6 is used, informed by a sample of paths generated in Google maps for similar neighbourhoods. This distance factor is varied with the change in Network type later in the experiments.

Problems with beeline distance factor

In the design experiments, the beeline distance factor is used as a proxy for ease of walking for pedestrians, and walkability of the network. By doing this, we run the risk of focussing our analysis on traffic flows, relegating pedestrian behaviour to the background. In future research, it is highly recommended to use the actual pedestrian network as a walking path, as shown in Figure 8.29, rather than calculating the walking distance from a beeline distance factor. In this case, the pedestrian link length can be weighted based on various parameters that influence walkability, such as shading, level of interest or greenery. A more nuanced understanding of pedestrian network design in relation to traffic flows can be obtained with this type of analysis.

Figure 8.27 Interior overview of the DART Module
Source: TUM CREATE, from https://www.tum-create.edu.sg/research/design-autonomous-mobility

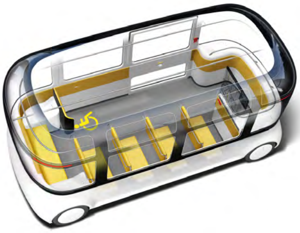


Figure 8.28 Bus and MRT lines in the site

Figure 8.29 Pedestrian Network in the base model

8.5 In summary

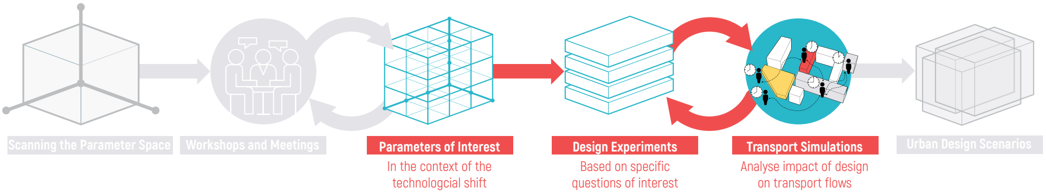
This chapter set up the foundations of the empirical part of this research. There is a large set of parameters that we can experiment with, which was reduced to a manageable size through stakeholder consultation. Four questions of interest were identified that form the basis of four design experiments. Demand responsive automated transit deployed in a fictional Singapore New Town was developed as the site of these experiments. Seven layers of information were created for a base model that can seamlessly communicate with the simulation model through a visual interface in Sketch MATSim. The simulation model was defined in MATSim using a certain initial demand and vehicle population that match the base conditions. This parametrised model is modular enough to be modified for design experiments, and Sketch MATSim is agile enough to enable multiple iterative cycles of design and simulations, demonstrated through the four design experiments in the next chapter.

9 Design Experiments

We will now use the parametric model constructed in the previous chapter to perform design experiments driven by the four questions of interest identified in section 8.1. In each experiment, this base model is tested against two alternative strategies using multi-agent simulations performed using Sketch MATSim. The experiment results contribute to the formulation of recommendation for the design of the network, PUDO, parking and intersections.

9.1 The four design experiments

Figure 9.1 Design experiments assessed using multi-agent simulations



The four design experiments are built using the base model developed in the previous section and assessed using multi-agent simulations, as shown in Figure 9.1. Let us revisit the four question of interest discussed in section 8.1.

1. How do we design the street network for new transportation systems?

2. In the event of the end of private car ownership and total vehicle automation, how will we access transport options?

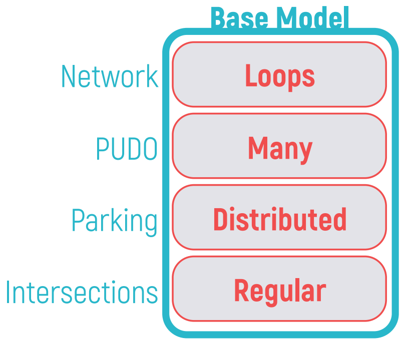
3. What will be the new requirements for parking infrastructure?

4. If AVs operate most efficiently when segregated from pedestrians, who gets priority on streets and intersections?

4 Experiments

Each question here relates to one design experiments: Network, PUDO, Parking and Intersection. In the base model, the network type is defined as *Loops*, which signifies a hierarchical structure with many loops and cul-de-sacs, that minimises through traffic, as described in section 8.3.3. The PUDO type is *Many*, which refers to the provision of several PUDO options, approximately two per precinct, as discussed in section 8.3.5. Parking type is *Distributed*, which refers to several dedicated parking structures for different facilities, shown in section 8.3.4. Finally, intersection type is *Regular* which refers to conventional signalised intersections. These conditions were assembled to generate the base model, as discussed in section 8.3.6. Figure 9.2 shows the values of the parameters in the base model. For each experiment, two alternative strategies will be tested against this base model.

Figure 9.2 Values of parameters in the base model

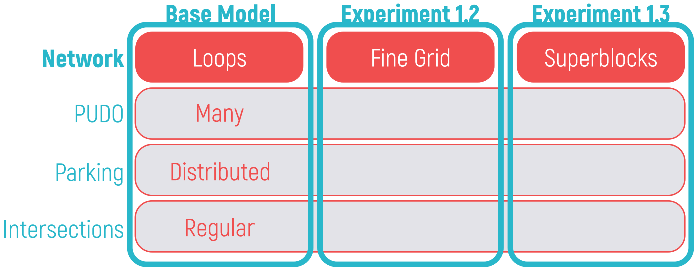


Experiments vs proposals

It is important to note that these design strategies must be seen in the context of an experiment, and not as an implementable strategy. In reality, design strategies cannot be implemented neatly as a 'type'. For example, a network can never be solely classified as a *Loop* or *Grid* but is usually a hybrid of different types. However, in these models, we construct a homogenous condition (for example, all intersections are signalised), and compare three extremes. These theoretical conditions provide us with structural results to study how each design strategy impacts transport flows. This is the reason why these models are not defined as proposals or scenarios, but as 'experiments'. We will now discuss the different strategies tested in the experiments and present intuitive conjectures on their performance.

9.1.1 Experiment 1: Network

Figure 9.3 Three network types in the network experiment



	Base Model	Experiment 1.2	Experiment 1.3
Network	Loops	Fine Grid	Superblocks
PUDO	Many		
Parking	Distributed		
Intersections	Regular		

Three Network Types

In the network design experiment, we test three network types – *Loops*, *Grid* and *Superblock*, shown in Figure 9.4, Figure 9.5 and Figure 9.6, respectively. While all other base conditions remain the same, we want to investigate how different network types impact transport flows, with shared and connected automated vehicles, as shown in see Figure 9.3. The street profiles, land use, parking and transit stop locations are maintained through all three models in the Network experiment.

Loops

The network in the base model is a *Loop* type which refers to a less connected network, with several T-junctions and dead ends, as shown in Figure 9.4. This network type is preferred for the design of New Towns since it discourages through traffic and reduces disturbance in residential neighbourhoods. A common critique of this network type is the lack of connections between neighbourhoods. All traffic is funnelled through the peripheral arterial roads which can act as a barrier between different neighbourhoods, creating a fracturing effect. Vehicular traffic is also forced to make many detours, which might increase Vehicle Kilometres Travelled (VKT), which we use as a proxy for vehicular emissions here.

Grid

Grid refers to a well-connected network, with mostly X-junctions, and a smaller distance between junctions, as shown in Figure 9.5. Grids are among the most typical forms of spatial organization used for planned urban expansion and can be considered the diametric opposite response to *Loops*. The distance between two major intersections is between 300-400 meters in *Loops*, while in *Grid* the block size is between 100-150 meters. Fine-grained grid with small block sizes is favoured by many urbanists and planners based on their apparent benefits for walkability (Boarnet and Crane, 2001; Jacobs, 1995, 1961). Ride pooling may also be more efficient in a grid network due to fewer detours. However, a higher number of intersections could present more points of conflict for pedestrians/cyclists. The through traffic could also be disruptive in quieter inner residential areas.

Superblock

The *Superblock* model is a variation of the *Grid* model with changes in maximum allowable speed as shown in Figure 9.6. We can assume 100% speed compliance here since connected vehicles can be governed through geofencing. The streets on the edges of the neighbourhood have a high-speed limit, while the internal roads have maximum allowable speed comparable to that of pedestrians and cyclists (10 km/hr). *Superblock* can be seen as a combination of *Loops*, with high-speed arterials and large block sizes, with a speed-restricted *Grid* inside. Since low-speed roads improve walkability and allow pedestrians to make more shortcuts, the beeline distance factor has been reduced to 1.3 in this model, compared to 1.6 in the base case. Such a network could increase the congestion on arterials. For a complete set of conjectures on the impacts of different network design strategies, see Table 9.1.

Table 9.1 Conjectures on the impact of network design strategies

		Loops		**Grid**		**Superblock**
Traffic Flow	🟥	No through traffic and more detours may create more congestion	🟦	Traffic flow may be better due to the availability of more route options.	⬜	Traffic mobility may be smooth on the arterial spine, but low on shared streets.
Active Mobility	⬜	Pedestrians may have to take long detours if pedestrian network follows traffic network	⬜	More connected network for pedestrians if the intersections are designed with pedestrian priority.	⬜	Pedestrian-friendly environment inside the block, but connections between blocks may be difficult.
Transit Access	🟥	Longer detours may lead to longer headways between transit vehicles. Walking time to transport hubs might be longer too.	🟦	Grid may improve access to transit due to fewer detours for shared vehicles and less walking time to transit hubs.	⬜	Depends on the location of mobility hubs and land use distribution inside the block.
Traffic Emissions	🟥	Potentially higher overall VKT due to longer detours	🟦	More route options, shorter detours will lead to fewer VKT.	🟦	May improve the fuel efficiency of AVs on arterial spines.
Space & Space Use	🟦	Slightly less road space may be required than in Grid	🟥	More space may be required for roads.	🟦	A significant amount of road space can be reclaimed

🟦 Expected Benefit 🟥 Expected Threat ⬜ Uncertain

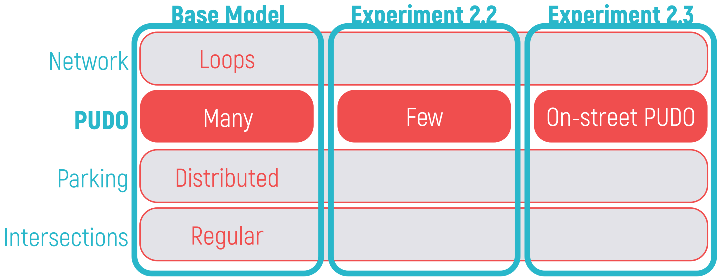
Figure 9.4 Network design of the ‘Loops’ Model

Figure 9.5 Network design of the ‘Grid’ Model

Figure 9.6 Network design of the ‘Supergrid’ Model

9.1.2 Experiment 2: PUDO

Figure 9.7 The PUDO experiment



	Base Model	Experiment 2.2	Experiment 2.3
Network	Loops		
PUDO	Many	Few	On-street PUDO
Parking	Distributed		
Intersections	Regular		

Three types of PUDO

The PUDO experiment comprises of three PUDO types – *Many*, *Few* and *On-street* PUDO, shown in Figure 9.8, Figure 9.9 and Figure 9.10, respectively. While all other base conditions remain the same, we want to investigate how different PUDO strategies impact transport flows, with shared and connected automated vehicles. The rest of the parameters remain the same as in the base model, as shown in Figure 9.7.

Many PUDOs

In the base model, *Many* PUDO bays are provided with a waiting area, as shown in Figure 9.12. Shared DRT service can only be accessed from one of these many pick-up and drop-off points distributed across the site, but private vehicles and taxis provide door to door service. The PUDO (shown in red) are much more closely spaced together than bus stops (shown in yellow). PUDOs have a large service area and short access times for users, providing almost door-to-door like service. The size of the bay required in this case could be smaller since the vehicles are distributed over many more points. However, with shorter distances between stops, and the additional time needed for deceleration, dwelling and acceleration at every stop, may increase overall travel time. A higher number of stops may also lead to less efficient ride pooling and more detours.

Few PUDOs

In the second model, much fewer PUDO points are provided, which are located on the three largest street types, as shown in Figure 9.9. There are a total of 33 PUDO points, implying a provision of about six dedicated DRT PUDO points per neighbourhood. *Few* PUDO points can be seen as integrated mobility hubs that consolidate PUDO activity from several locations. Such consolidated hubs need to be larger and may increase the access time for pedestrians. However, longer distance between stops allows small AVs to operate in platoons.

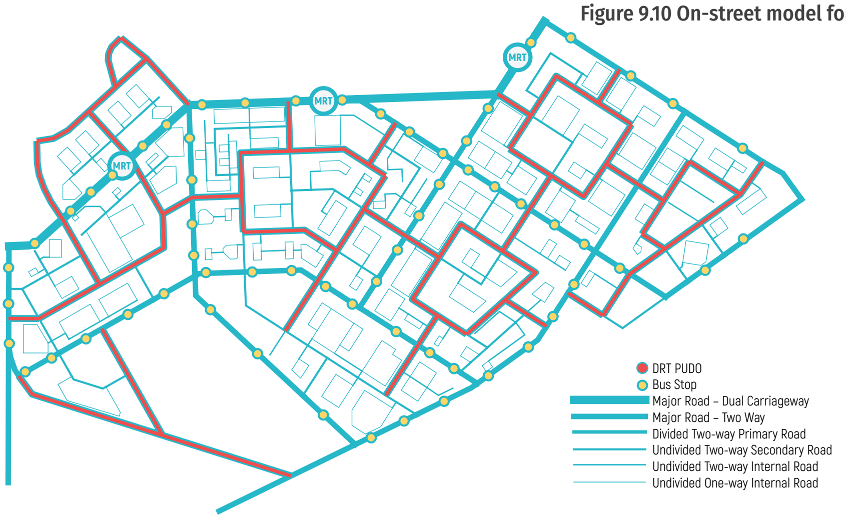
Ride consolidation with few PUDOs

Consolidation of rides also leads to fewer detours, making ride-pooling much more efficient. The difference between the paths of a shared vehicle with *Many* PUDO points and with *Few*, is shown in Figure 9.11. On the left, the vehicle makes long detours to serve four riders (shown as a circle), going to two destinations (shown as a square). On the right, the detours reduce significantly if the riders walk two blocks to designated PUDOs.

Figure 9.8 ‘Distributed’ Model for the ‘PUDO’ Experiment

Figure 9.9 ‘Consolidated’ Model for the ‘PUDO’ Experiment

Figure 9.10 On-street model for the PUDO experiment



On-street PUDOs

The third strategy is *On-Street* PUDO, where the lane closest to the sidewalk is used as a stop-and-go lane for PUDO activity. The primary difference between the *Few/Many* PUDO strategy and *On-street* PUDO is that the former are organised in bays (see Figure 9.12). In the *On-street* PUDO shown on the left, the traffic flow capacity is effectively reduced in half, since one lane is blocked for PUDO activity. On the right in bays, traffic flow is unaffected during pick-up activity, since the vehicle exits and re-enters the traffic flow to pick-up passengers. In the model, PUDO activity is only allowed on those streets that have more than one lane per direction, that do not have bus stops and that are not expressways. These restrictions leave only type 3 streets, which amounts to about 36 total lane kilometres in the model, as shown in Figure 9.10.

Conjectures on benefits and threats of on-street PUDO

On-street PUDO does not need dedicated infrastructure and is, therefore, the most space and cost-efficient strategy. The PUDO lane can also double up as a parking lane depending on the traffic flow on the street. It is expected that with vehicle automation and increased sharing, substantial gains will be made in street capacity, and one lane could be blocked for PUDO activity, without significantly disrupting the traffic flow. The vehicles may also travel faster since they do not need to exit and re-enter the traffic flow. However, it is unclear if there is enough street space available to conduct PUDO activity, and to what extent it would disrupt the traffic flow. On-street PUDO activity may also conflict with bicycle traffic. For a complete set of conjectures on the impacts of different PUDO design strategies, see Table 9.2.

Figure 9.11 Distributed PUDO points (left) vs Consolidated PUDO hubs (right)
Red represents vehicle movement path, and the dotted blue line is the walking path.

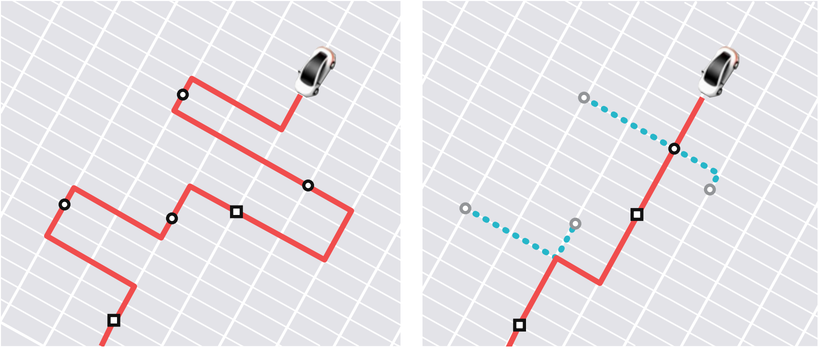


Figure 9.12 Difference between on-street PUDO (left) and Bay-based PUDO (right)
Yellow represents the pedestrian area, red is PUDO area, and grey is the traffic lane.

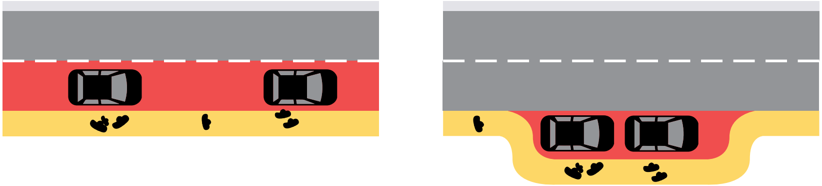


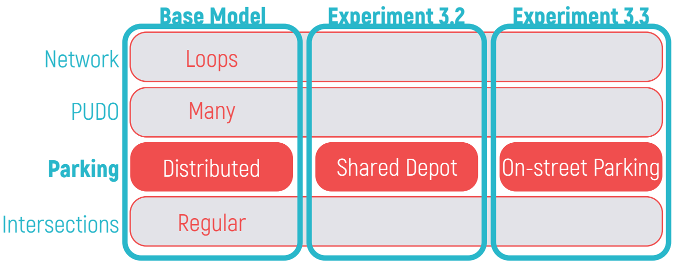
Table 9.2 Conjectures on the impact of PUDO design strategies

	Many	Few	On-Street
Traffic Flow	🟥 Shared vehicles may have to make many detours and stop more often creating congestion.	🟦 Vehicles stop less often and make fewer detours, which may make traffic flow smoother.	⬜ If the capacity of the street is reduced by one lane, it might lead to congestion. But since vehicles do not exit and re-enter flow they might be faster.
Active Mobility	🟥 Easy access to shared vehicles may make it more attractive than walking/ cycling.	🟦 Fewer conflicts of PUDO points with bicycles.	🟥 On-street PUDO lane may impede bicycle mobility.
Transit Access	🟦 PUDO points are easily accessible to all travellers.	🟥 Fewer PUDO points may not serve the entire area uniformly.	🟦 Vehicle may be more easily accessed from the street.
Traffic Emissions	🟥 Shared vehicles may have to make many detours, increasing VKT.	🟦 More rides may be consolidated, with less detours, fewer VKT. May be more fuel-efficient due to less stopping.	🟦 Vehicles may travel fewer kilometres overall.
Space & Space Use	⬜ PUDO points are smaller in size but larger in number.	⬜ PUDO hubs are larger in size but fewer in number.	🟦 Under-utilised street lane can be used for PUDO activity reducing the requirement for dedicated PUDO area.

🟦 Expected Benefit 🟥 Expected Threat ⬜ Uncertain

9.1.3 Experiment 3: Parking

Figure 9.13 The Parking Experiment



	Base Model	Experiment 3.2	Experiment 3.3
Network	Loops		
PUDO	Many		
Parking	Distributed	Shared Depot	On-street Parking
Intersections	Regular		

Three parking strategies

In the Parking experiment, we test three types of parking strategies – *distributed* parking structures, *shared parking depots* and *on-street parking*, as illustrated in Figure 9.14, Figure 9.15 and Figure 9.16. The rest of the parameters are the same as in the base model, as shown in Figure 9.13.

Figure 9.14 ‘Distributed’ Model for the ‘PUDO’ Experiment

Figure 9.15 ‘Consolidated’ Model for the ‘PUDO’ Experiment

Figure 9.16 On-street model for the PUDO experiment

Distributed Parking

Distributed parking strategy is the base condition where several facility-specific parking structures are distributed across the site, which is the current convention in Singapore. Dedicated parking structures are built and managed by different private or public entities that do not coordinate parking management leading to a massive under-utilisation of space. While residential lots remain empty during day time, those in business districts are underused at night time or during weekends. Since automated vehicles can park themselves, this may eliminate the need for a dedicated parking space at every destination. A vehicle can drop the user off at work, for example, pick up groceries at a shop, and park at home again. While this saves space, it can lead to more VKT, emissions and congestion. In this model, some existing small parking lots allow parking for shared vehicles (shown in red), and parking space allocation is coordinated from a single dispatcher to maximise efficiency.

Shared Depot Parking

With greater vehicle sharing, the demand for private parking spaces may go down considerably, leading to the emergence of shared *Depots*, the second strategy being tested in this experiment. Fewer but larger parking depots can be provided instead of many small parking structures. Shared automated vehicles can drive to the passenger quickly from remote parking lots, freeing up valuable real estate in the centre of the city. This strategy would also lead to a consolidation of investment in electric vehicle charging facilities. However, it may generate empty VKT, and increase the waiting time for passengers requesting a ride. Here DRT parking is only allowed in three large parking depots (half a depot per neighbourhood). These shared parking structures are located at the periphery of the site, as shown in red in Figure 9.15.

On-street parking

The third strategy is to not provide any dedicated parking structure but allow vehicles to park in one lane on the street. It is expected that with vehicle automation and increased sharing, substantial gains will be made in street capacity, freeing up space for parking on the street. Same as with on-street PUDO, parking is only allowed on streets with more than one lane per direction, and streets that do not have bus stops and are not expressways. These restrictions leave only Type 3 streets for parking, which amounts to a total of 36 lane kilometres. *On-street* parking could ease vehicle access by eliminating access and egress time to and from dedicated parking lots, and could eventually double up as on-street PUDO, reducing the spatial imprint of transportation infrastructure even further. However, it is unclear if the street capacity gains from the technological shift are sufficient to accommodate the entire vehicle fleet on-street. Parking lanes may also conflict with bicycle lanes, depending on the design of cycling infrastructure. For a complete set of conjectures on the impacts of different parking design strategies, see Table 9.3.

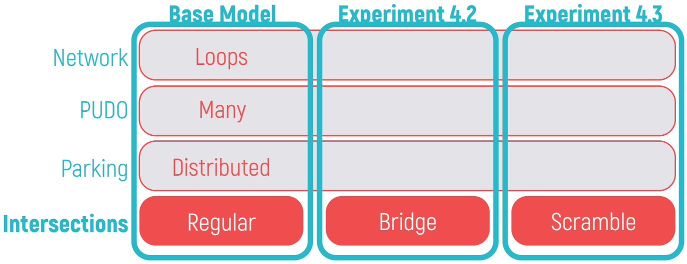
Table 9.3 Conjectures on the impact of parking design strategies

		Distributed		Shared Depots		On-Street
Traffic Flow	🟦	Vehicles cruise less, improving the traffic flow.	🟥	Vehicle may cruise empty leading to congestion.	🟥	Street capacity may reduce, causing congestion.
Active Mobility	⬜	-	⬜	-	⬜	Parked vehicles on street may act as a buffer between pedestrian and traffic but may conflict with cycle lanes.
Transit Access	🟦	Vehicles may be available quicker because of proximity to parking.	🟥	Waiting time for vehicles might be more due to the long distance to depots.	🟦	Parking access and egress time is saved, may lead to quicker arrivals.
Traffic Emissions	🟦	Vehicles have to cruise less for parking and may reduce overall VKT.	🟥	Empty VKT may increase.	🟦	VKT may reduce if driving to and from parking is eliminated.
Space & Space Use	🟥	May require more space.	🟦	Less space may be required.	🟦	One lane on the street can be used for parking, freeing up existing parking infrastructure for redevelopment.

🟦 Expected Benefit 🟥 Expected Threat ⬜ Uncertain

9.1.4 Experiment 4: Intersections

Figure 9.17 Intersection Design Experiment



	Base Model	Experiment 4.2	Experiment 4.3
Network	Loops		
PUDO	Many		
Parking	Distributed		
Intersections	Regular	Bridge	Scramble

Three intersection strategies

All intersections in the base model are *Regular* signalised intersections, where pedestrians and traffic flow are given access to pass through in a phased manner. The timing of the signal can be adjusted to give priority to vehicles or pedestrians. In the base case, both vehicles and pedestrians are given equal priority. The two other strategies tested in the design experiment are *Bridge*, which gives priority to vehicular traffic, and *Scramble*, which gives priority to pedestrians, as shown in Figure 9.17. All three strategies are illustrated in Figure 9.18.

Bridge intersection

Bridge refers to the complete separation of pedestrians and vehicles at intersections through overpasses or underpasses to improve traffic flow. One of the basic rules of robotics is that the simpler and more predictable the environment, the easier it is to build software to enable a robot to navigate that environment (Lipson and Kurman, 2016). Streets and intersections involve complex non-verbal social interactions between the vehicle and pedestrian, which is hard to replicate with automated vehicles. Therefore, to maximise the efficiency of AVs, it is preferred to have physical separation from pedestrians at intersections, so that vehicles can better coordinate their movement and maximise the throughput. In this model, all major traffic intersections with road types 1-3 have overhead bridges for pedestrians to cross. Intersections on smaller roads are signalised.

Slot based intersections

Connected and coordinated vehicles can cross the intersection without stopping through an SI system, eliminating the need for traffic signals and doubling the intersection capacity (see (Tachet et al., 2016)). However, for pedestrians, these intersections are not as seamless, since bridges act as an obstacle and are sometimes perceived as twice the actual walking distance (Erath et al., 2017). Large overpasses bridging across high-speed traffic can be detrimental to street life as well. Since pedestrians have to walk much longer in this model, the beeline distance factor is increased to 2, compared to 1.6 in the base case.

Scramble intersection

Scramble is the third design strategy which unlike *Bridge* prioritises pedestrian flow over vehicular traffic. It is a signalised traffic intersection where the movement of all vehicular traffic is temporarily stopped, thereby allowing pedestrians to cross an intersection in every direction, including diagonally. All intersections on road types 1-3 have pedestrian priority signals with scramble crossings. Intersections on smaller roads are non-signalised with pedestrian priority.

Changes in traffic throughput and beeline factor

Here, the traffic signal phase for pedestrian flow is longer than that of traffic flow. Thus intersection capacity is reduced to 90% of the base model. Traffic throughput in locations with scramble crossing can be much lower than 90% at signalised crossing today. However, here we assume a higher throughput than usual since in the green phase, connected AVs are still expected to follow a slot-based system. The beeline distance factor is reduced to 1.3, compared to 1.6 in the base model. Scramble crossings need to be designed in such a way that pedestrians are always separated from fast-moving vehicular traffic at a safe distance. For a complete set of conjectures on the impacts of different intersection design strategies, see Table 9.4.

The four experiments discussed here were simulated using Sketch MATSim and evaluated against various criteria. The next section outlines the key findings from each experiment.

Figure 9.18 Three intersection strategies tested

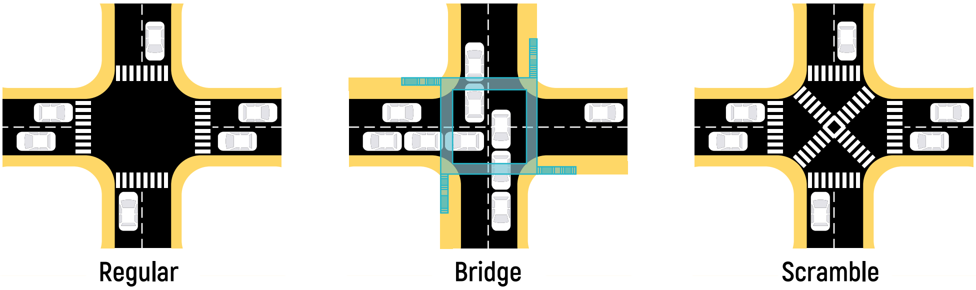


Table 9.4 Conjectures on the impact of Intersection design strategies

	Regular	Bridge	Scramble
Traffic Flow	⬜ Traffic flow would remain relatively stable	🟦 Vehicles may move faster and more efficiently. Intersection capacity may increase twofold.	🟥 Traffic stops more often at intersections, hence traffic flow may be reduced.
Active Mobility	⬜ Depending on traffic light phase settings, walking time could increase or decrease	🟥 Crossing bridges is considered tedious and time-consuming, hence may hinder active mobility.	🟦 Pedestrian priority infrastructure may foster active mobility.
Transit Access	⬜ -	⬜ Longer crossing times may lead to difficulty in accessing transit.	🟦 Pedestrian priority infrastructure will make transit hubs easy to reach.
Traffic Emissions	🟥 Since vehicles have to stop more often, fuel efficiency may be lower.	🟦 Vehicles stop less frequently at intersections and travel at high speed, leading to better fuel efficiency.	⬜ Active mobility mode share might increase, leading to less VKT.
Space & Space Use	⬜ No change in road space usage expected	🟦 AV priority will allow vehicles to move faster and closer saving street space. They would also allow for more compact non-signalised intersections.	⬜ Significant road space-saving benefits cannot be expected unless a modal shift is encouraged.

🟦 Expected Benefit

🟥 Expected Threat

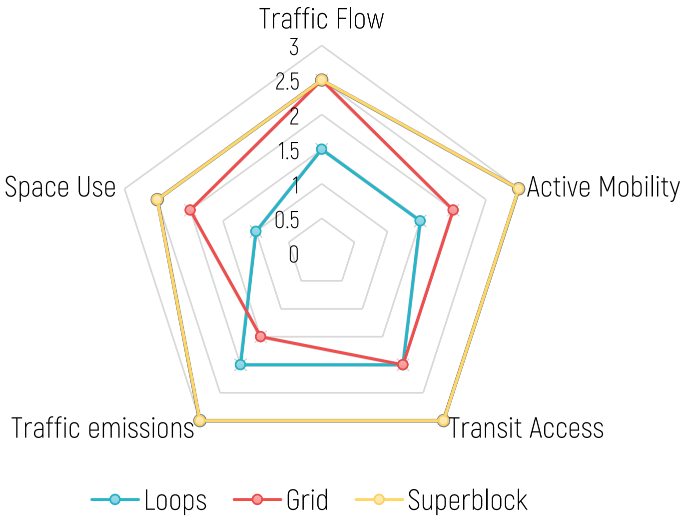
⬜ Uncertain

9.2 Which network design performs best?

Superblocks perform best

On most metrics, *Superblocks* perform better than the *Loops* and *Grid*. Based on the results from the simulation, the three network types have been scored on a scale of one to three, three being the best performance and one being the worst, as shown in Figure 9.19. Three primary conclusions can be drawn from this experiment. First, the disconnected *Loop* network which is prevalent in most HDB towns in Singapore currently suffers from the lack of efficient first/last mile solutions, and this remains a problem despite the implementation of demand responsive transit. Second, a more connected network topology does not necessarily mean more vehicle sharing, and could even result in more VKT. Finally, we find that under some circumstances, the slowest network by speed can ironically have the fastest overall travel times. We will now discuss these three conclusions in more detail.

Figure 9.19 Comparison of performance of three network types



9.2.1 First/last mile connectivity the biggest challenge in Loops

Initial iterations

A hierarchical network with disconnected topology, as represented by the *loops*, does not perform well with dynamically routed small-sized shared vehicles. In the first iteration, the three network strategies were simulated in Sketch MATSim with six-seater DRTs. These vehicles are similar in size to the 4-seater human-driven cars of today. Initially, a smaller fleet size led to a high rejection rate[3] for DRT and taxi (up to 43%) and a larger fleet size clogged the network. Eventually, small size vehicles were deemed unsuitable for the disconnected loop network structure. It must be noted that in reality if a certain portion of the demand is not served in time, the agents would change their plan and eventually make the right choice in more iterations. As we head to infinite iterations, more people make successful plans.

Vehicle size of fleet selected

After several iterative cycles, a vehicle size of 20 passengers and a fleet size of 360 was arrived at for *Loops*. For the more connected *grid* and *superblock* networks, smaller, more agile six-seater vehicles were used. The fleet size of these six-seaters was expanded to 1000 vehicles to keep the total seating capacity comparable between networks. Despite these changes, the rejection rate for DRT service remains the highest in *loops*. As shown in Figure 9.20, 25% of all DRT requests are rejected in Loops, and the total number of accepted rides remains the lowest of all three models.

First/last trips underserved, car trips rise

In the simulation results, we can see the gap in first/last mile connection options, which the DRT is expected to fill. Loop type network topology results in a high detour ratio, highest among all models at 2.09 (mean). Consequently, in-vehicle travel time for DRT is also the highest at 15.5 minutes, nearly 50% higher than the other two models. Despite high distance-based occupancy rates of the DRT vehicles (highest at 6.8 mean persons per DRT vehicle), DRT mode share remains one of the lowest. At the same time, private car ridership is one of the highest, accounting for 21% of all trip legs[4] in *Loops*, compared to 19% in the other two networks, as shown in Figure 9.21. In absolute numbers, DRT trips are the lowest as well, at about 120K, while those for *Grid* and *Superblock* are approximately 124K and 139K respectively.

More bus use and walking, but high walking time

The travellers in *Loops* instead choose to use buses or walk to their destination. As shown in Figure 9.21, bus legs are somewhere in between *Grid* and *Superblock*. Walking rate is also slightly higher in *Loops* than in *Grid* but lower than *Superblock*. The average walking time to transit in *Loops* is the longest at 8 minutes (about 400 meters) which is quite substantial for a tropical country like Singapore. Consequently, travellers shift to private cars as soon as they have it available as an option, which leads to the generation of the highest VKT by car, as shown in Figure 9.22. It must be noted that 'walk' here mainly refers to access and egress. Agents will only opt for a direct walk between origin and destination if the trip is short enough that taking transit does not improve their travel time.

More space consumption

Loops network also loses out in terms of space consumption. More road space is required overall as compared to the grid and superblock networks, as shown in Table 9.5. Additionally, more space is also required for pick-up and drop-off activity since the DRT vehicles are bigger in this model. These larger vehicles are not used as intensively, with the average occupancy rate being 6.8 persons for vehicles that can accommodate up to 20 people. Thus, it is very challenging to implement DRT as a first/last mile solution in a disconnected network topology such as that in Singapore HDB New Towns.

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[3] When a user requests a DRT, the router searches for vehicles within 7 minutes' travel time from the user (this is pre-calculated based on link travel time in the previous iteration). If no vehicle can reach the user within 7 minutes, the DRT request is considered 'rejected'. Eventually, the user may have to wait longer than 7 minutes due to congestion. Rejection rates can be very high if there is a high level of congestion or low provision of vehicles.

[4] A trip is the direct travel between two destinations with one or more transport modes. An example for a trip is home to work. A trip leg is a segment of a trip, which is separated by a change of transport mode or an intervening stop with a short dwell time (e.g. stop for a coffee, public transport transfers)

Figure 9.20 Comparison of total DRT rides and rejection rates in Loops, Grid and Superblock

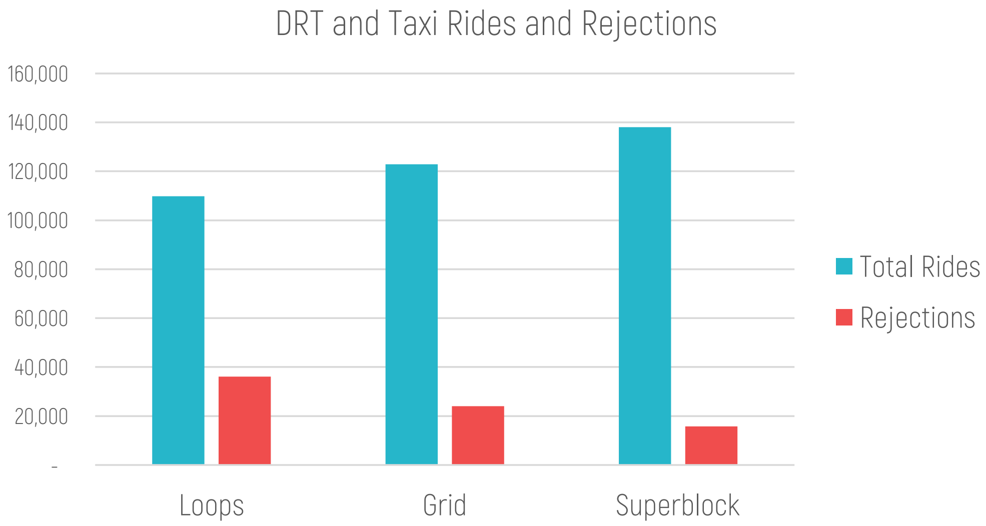


Figure 9.21 Comparison of trip legs by mode in all three network types

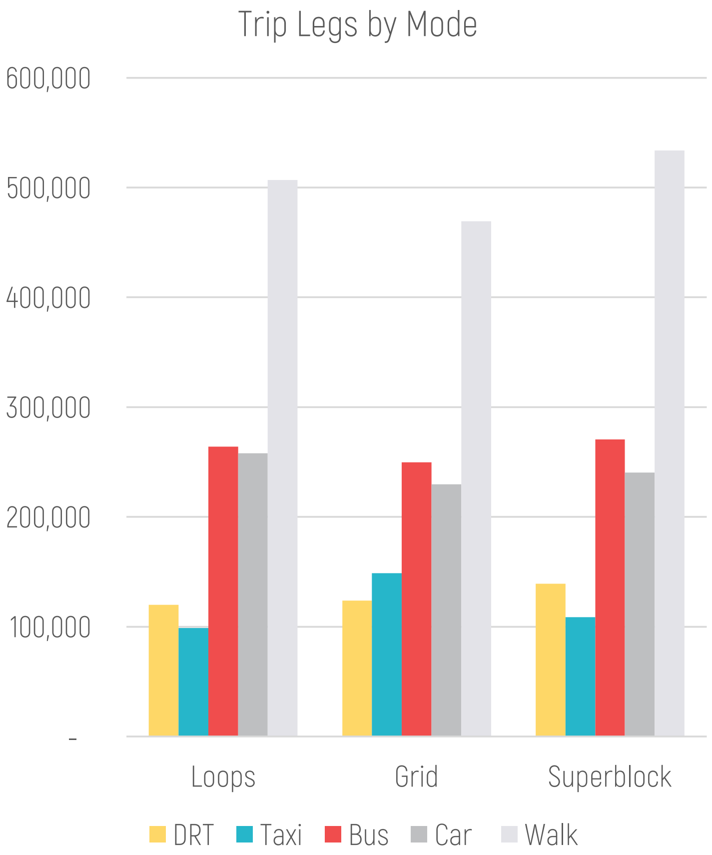


Figure 9.22 Comparison of VKT generated

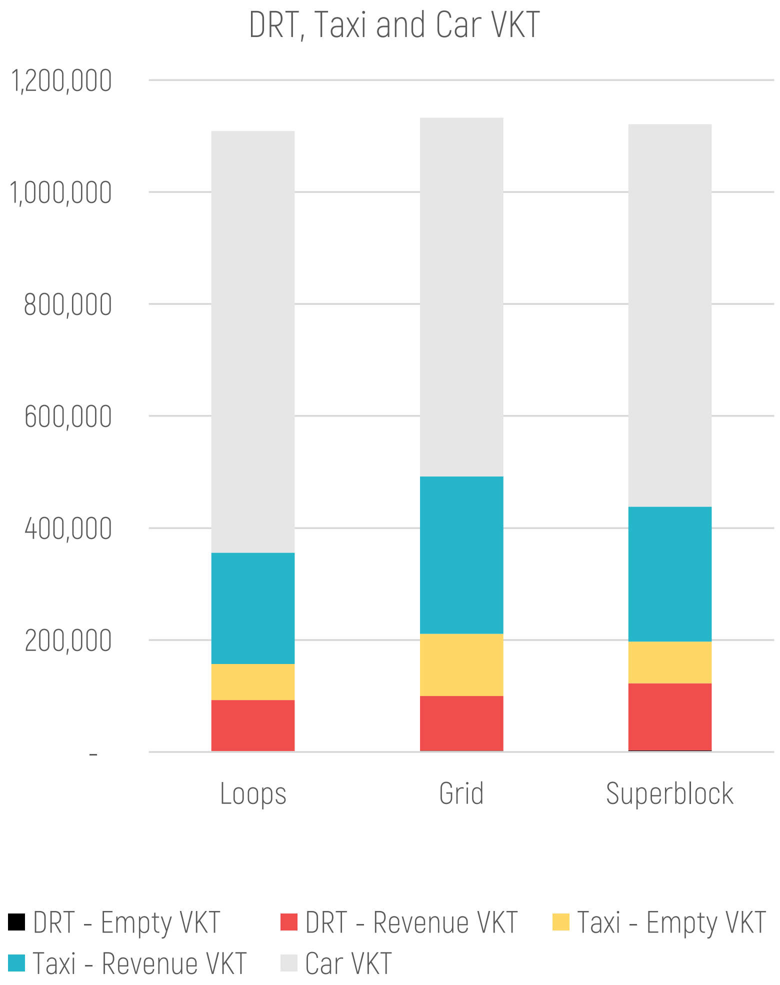


Table 9.5 Road space consumptions by the three different networks

	Loops	Grid	Superblock
Total road area (sqkm)	1.65	1.63	1.11
Total Lane kilometres	250	237	167.5

9.2.2 The extra kilometres generated by the well-connected grid

DRTs do not perform well in grid

The *Grid* network is expected to provide better mobility for all modes by being better connected, allowing fewer detours and shorter travel distances, as per the speculations in Table 9.1. This assumption was found to be true in the design experiment. The mean travel distance for all DRT vehicles is 3.86 km, as compared to 5.67 km for Loops. The detour ratio is considerably lower as well, which is why DRTs are expected to perform well in this model. However, that was not found to be the case.

Grid works well for taxis

Taxi is the mode of choice in *Grid*, with almost 12% of all trip legs travelled by taxi, as compared to 8% in *Loops* and *Superblock*, as shown in Figure 9.21. The taxi use is so high that it drives down the use of all other modes including, significantly, cars. Private car VKT is the lowest in this model, compared to the other two, as shown in Figure 9.22. One explanation for this could be the fact that while car costs are sensitive to distance travelled, taxi costs are more sensitive to travel time. Thus if there is no congestion, taxi costs can be comparable to that of a private car, especially so with vehicle automation. In fact, for shorter trips, a taxi can sometimes even be cheaper than a private car. In *Grid*, this is undoubtedly the case, since the mean in-vehicle travel time is the shortest at 10 minutes, compared to 15.5 and 11.2 in *Loops* and *Superblock* respectively. While the DRT usage is higher in *Grid* than in *Loops*, taxi use is much more dominant in *Grid*, evident in the comparison of the dwelling time of different types of vehicles at PUDO and bus stops, shown in Figure 9.23.

High waiting time in grid

An unexpected consequence of short trips and high taxi use is the increase in waiting time for vehicles in *Grid*, which is the highest at more than 5 minutes on an average. Such high waiting times may seem counter-intuitive at first, since distances between locations are much shorter in a more connected network, and travel time is the shortest in the *Grid* compared to the other models. At the same time, taxi use is so high that vehicles are occupied much more. When a person requests a ride, the taxi might be fulfilling another request at that moment. However, the rider is willing to wait longer, since in-vehicle travel time is the shortest in *Grid*.

High VKT, low occupancy

High taxi use leads to a surge in VKT. The mode share for buses is the lowest, and fewest walking trips made in *Grid*, despite much lower average walking time (6.6 minutes) compared to *Loops*, as shown in Table 9.7. We initially expected better bundling of rides with a connected grid, which is partially seen in the simulation results. The distance-based average occupancy of the six-seater DRT vehicles is quite good at 4.84. However, when this is combined with taxis, the total distance based occupancy of all shared vehicles goes down dramatically, even lower than in *Loops*, as shown in Table 9.8.

Reimagining the 'taxi'

One could argue that the vehicle kilometres driven by taxis serving these very short last-mile trips should not necessarily be considered a negative indicator. Given the occupancy and distance travelled, these 'taxis' could very well be imagined as a smaller, less space-consuming vehicle that runs on clean fuel. However, it must be noted here that of all the VKT generated by taxis in *Grid*, almost 25% is empty VKT. Even if a vehicle runs on clean fuel, having almost a quarter of all VKT being empty is not ideal. Alternatively, we can consider another mode that can serve such one person short trips effectively in the most space-efficient and environmentally sustainable way – the bicycle. With a more connected grid, well-designed infrastructure for active mobility (bicycles or PMD) is a necessary complement.

Table 9.6 Road space consumptions by the three different networks

	Loops	**Grid**	**Superblock**
Mean distance travelled/ride (km)	5.67	3.86	3.70
Mean direct distance/ride (km)	2.71	2.08	2.32
Detour Ratio	2.09	1.85	1.59

Figure 9.23 Comparison of dwelling time of shared vehicles at PUDO and bus stops

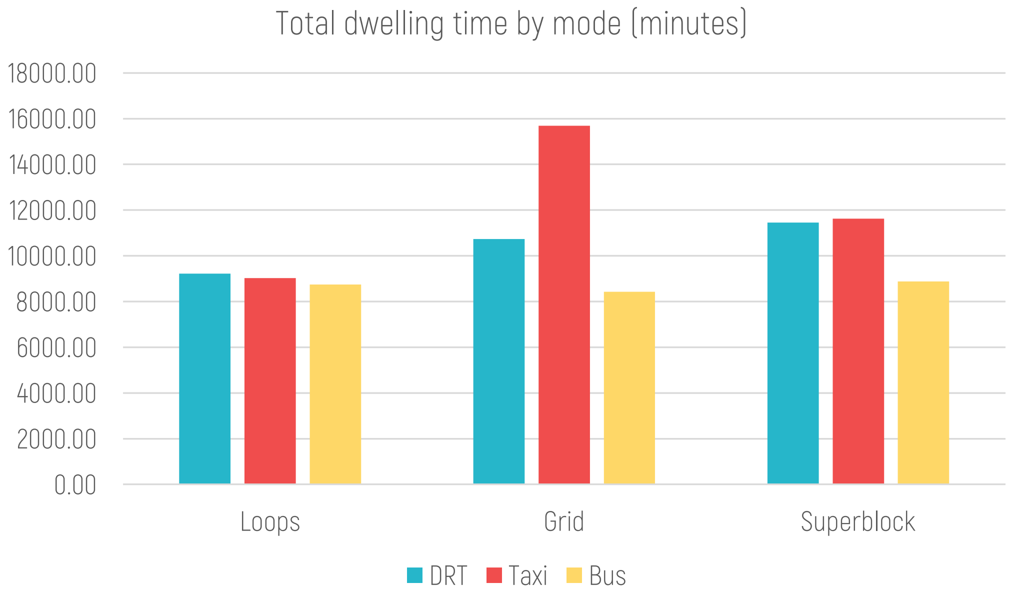


Table 9.7 Total, average and median walking time to transit in all three networks

	Loops	**Grid**	**Superblock**
Total walking time to transit (hr)	11924	19836	19111
Average walking time to transit (m)	8	6.60	5.68
Median walking time to transit (m)	5	5.40	4.45

Table 9.8 Distance-based occupancy of shared vehicles in all networks.

	Loops	**Grid**	**Superblock**
Distance-based occupancy (DRT)	6.8	4.84	4.27
Distance based occupancy (DRT+Taxi)	2.83	1.99	2.08

Table 9.9 Observed traffic speeds during peak and off-peak hours on the three networks

	Loops	**Grid**	**Superblock**
Avg network freespeed*	42.77	41.30	29.03
Avg Network Peak Speed*	38.89	38.56	26.68
Length wtd Avg off-peak speed*	40.60	39.88	27.66
Avg peak speed/free speed	0.93	0.94	0.95
Avg off-peak speed/free speed	0.96	0.97	0.98

* Average of average speed on all links, weighted by link length

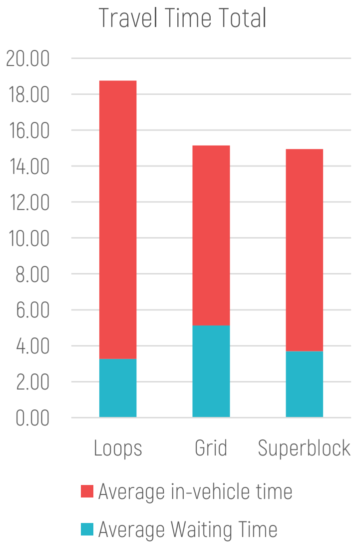


Figure 9.24 Comparison of DRT travel times in the three network types

9.2.3 Can slower speeds lead to faster travel?

Shorted walking makes all shared modes perform well

The *Superblock* functions well on almost all metrics. The slow traffic speed inside the superblock allows pedestrians to take shorter routes to transit stops, which is why the beeline distance factor was reduced in the simulation as an input. Improvement in walkability has a much stronger effect on improving vehicle sharing and transit ridership than creating a more connected network topology. All shared modes perform well in *Superblock*, with the highest number of trip legs made with DRT, public transit and walking, as shown in Figure 9.21. When shared modes perform well, overall VKT generated is much lower than those in *Grid* (but still higher than *Loops*, since more trips are made overall). Overall empty VKT generated as a percentage of total VKT is also the lowest in *Superblocks* at 17.7%, as shown in Figure 9.22.

Fuller vehicles, smaller detours, fastest travel time

It is interesting to note that the detour ratio is the smallest in *Superblocks*, even smaller than in *Grid*, even though the two have exactly the same network topology (see Table 9.6). Additionally, not only are there more DRT trips made as an absolute number, but the DRT rides are also much fuller in *Superblocks*, with the highest overall distance-based occupancy (slightly lower than *Grid* for DRT only), as shown in Table 9.8. The overall travel time is also the fastest in the *Superblock*, as shown in Figure 9.24. The waiting time in *Superblock* is slightly higher than in *Loops*, and the travel time is slightly higher than in the *Grid*. But the total travel time as a sum of waiting time and in-vehicle travel time is the lowest in *Superblock* of all three networks.

Slowest network but not the most congested

Lowest travel time in *Superblock* is surprising given that it has a 'slow' network by design. Table 9.9 shows the average free speed and observed speed during peak and off-peak hours on all links weighted by link length in the three models. We can see that while the allowable free speed on *Loops* and *Grid* are comparable (*loops* even being slightly faster than *Grid*), *Superblock* is radically slower, by almost 30%. Similarly, the mean observed speed during the peak and off-peak hours in *Superblock* is more than 30% slower than in *Loops* and *Grid*. However, the network performance, which defined here as the average of the ratio of observed peak speed to free speed for every link, is the best for *Superblocks*. When we compare the link performance for all three models in Figure 9.25, it is clear that the *Superblock* is slower, but not congested.

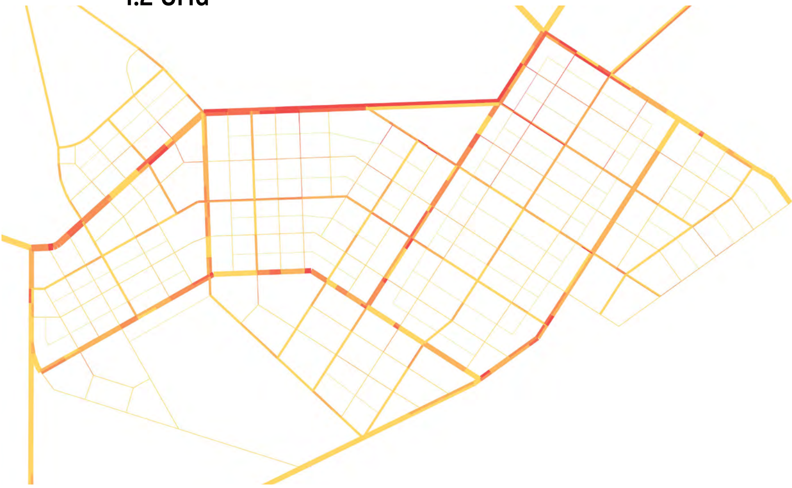
Space requirement

We can conclude that improvements in walkability and network connectivity has a cascading effect. As DRT suddenly becomes a viable last-mile solution, it dramatically drives up ridership of all shared modes, including transit. High usage of buses and DRT of course, drives up the space requirement for PUDO and bus stops, which is the highest in *Superblock* among all networks. However, this space consumption is negligible compared to the road space saved, as shown in Table 9.5.

Figure 9.25 Comparison of Network performance for all three network types

1.1 Loops

1.2 Grid



1.3 Superblock

9.2.4 Summary

A summary of the simulation results for the three network models is given in Table 9.10.

Table 9.10 Results from the Network Experiment

	Loops	Grid	Superblock
Traffic Flow	🟥 Traffic flow is hindered as a result of disconnected network	⬜ Traffic flow is good but network performance is not the best of all three models	🟦 This network is the slowest but performs the best in terms of the ratio of peak speed to free speed.
Active Mobility	🟥 The walk to transit access points and facilities is the longest, discouraging people from walking.	⬜ Walking time is shorter than loops, but total walking trips are lowest here, because of the attractiveness of private modes.	🟦 Shortest walking distance and most walking trips
Transit Access	⬜ DRT performance suffers due to detours and lack of connectivity, but bus performs slightly better	⬜ DRT usage is better here than in loops, but transit use is not so high	🟦 Shortest overall travel time and highest usage of DRT and bus
Traffic Emissions	⬜ Private cars generate high VKT but total VKT is not the highest	🟥 Lowest private car use but highest taxi use and high empty km generated, leading highest overall VKT.	🟦 Least empty VKT
Space & Space Use	🟥 More road space and PUDO space required	⬜ Slightly less space needed than in loops and lesser space required for PUDO	🟦 Least road space needed, but high PUDO space needed

🟦 Highest Score 🟥 Lowest Score ⬜ Medium Score

9.3 Which PUDO strategy performs best?

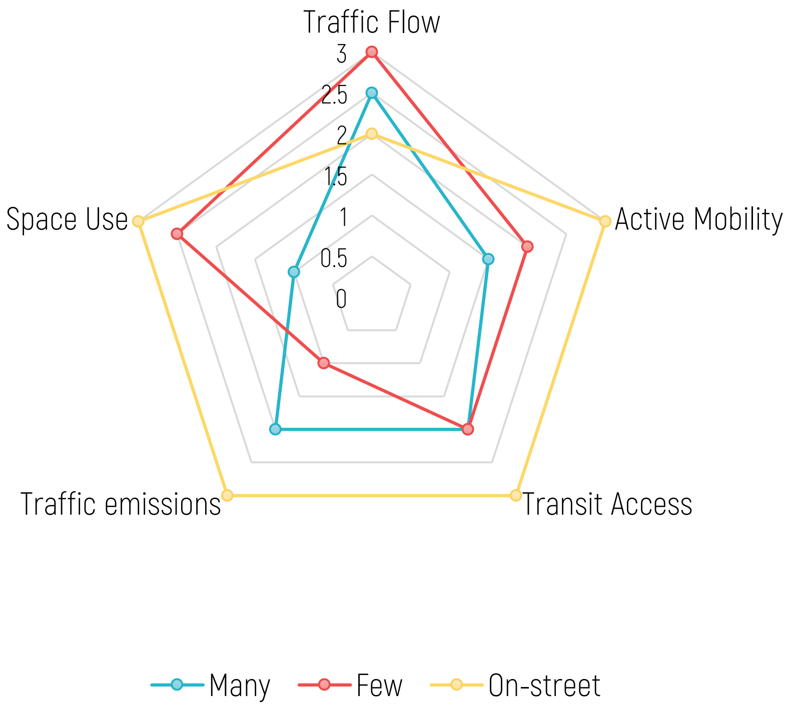
All three strategies perform well on different metrics

All three strategies, *Many*, *Few* and *On-street* PUDO, perform moderately well, depending on whether we are concerned with the performance of taxis, regular fixed-route transit or DRTs. Figure 9.26 shows a comparison of the three PUDO strategies on a scale of 1-3, 3 being the best performing strategy. Both *Few* and *On-street* are favourable strategies to implement, in different contexts. *On-street* may be challenging to implement in an already overburdened network, and *Few* may result in even more private car use if pedestrian connectivity is not enhanced. However, providing many PUDOs seems to be the least beneficial strategy.

Three conclusions

There are three main conclusions in this experiment. First, with many PUDOs, we get a high level of service for taxi and DRT through shorter waiting times. However, this requires a large amount of PUDO space and generates the highest VKT. Second, fewer PUDOs make buses very competitive, driving up transit ridership, also requiring lesser space. Surprisingly, the average size of the PUDO is also not much larger in *Few* than in *Many*, even though each PUDO serves more vehicles in *Few*. Finally, on-street PUDO combines benefits of both *Many* and *Few*, providing similar levels of service as *Many*, with better bundling of shared rides, like in *Few*. We will now discuss these conclusions in detail.

Figure 9.26 Comparison of performance of three PUDO types



9.3.1 Many PUDOs, many VKT

Smaller wait, but more travel time

When more locations are available to access DRTs, they are used more often, as expected. In *Many*, more trip legs are made by DRT than in *Few*. The primary advantage of having many PUDOs is shorter wait times for vehicles and shorter walking distance to transit. The average waiting time is lowest in *Many*, at 3.2 minutes, as indicated by the blue bar in the chart in Figure 9.27. However, the in-vehicle travel time is not the lowest, at 15.5 minutes on average which is lower than with *Few* PUDO but higher than *on-street* PUDO. Are the gains in waiting time and travel time enough to induce a mode shift from cars and taxis to shared modes?

Highest VKT with many PUDOs

Compared to *Few*, we see more trip legs for DRT (see Figure 9.28), and fewer trips for cars in *Many*. Nevertheless, the overall VKT generated remains the highest with many PUDOs. There are two reasons for this. First, the presence of many PUDOs reduces transit ridership. *Many* has the fewest bus trip legs of all models and the lowest bus dwell time (see Figure 9.30), an indicator of how full the buses are. Second, if we have more PUDO options available, the bundling of shared rides becomes less efficient. The occupancy rates of DRT in *Many* is the lowest at 6.4 persons per vehicle, compared to more than eight persons per vehicle in the other two models, as shown in Table 9.11. Even if we have more DRT rides in *Many*, the DRT itself is emptier, generating more vehicle kilometres.

Highest space requirement

The space required for PUDO is also the highest with many PUDOs, as expected. The total maximum dwelling length required is almost 280% that required with few PUDOs, as shown in Table 9.12. There are 99 exclusive DRT PUDO points, with a maximum dwell length of 22.3 metres on an average. The largest PUDO is 56 m, which means at a maximum seven DRT vehicles are performing pick-up/drop-off activity at this PUDO. Such a large space requirement for PUDO activity can be problematic for a land-scarce city like Singapore.

Figure 9.27 Average waiting time and in-vehicle travel time for all PUDOs

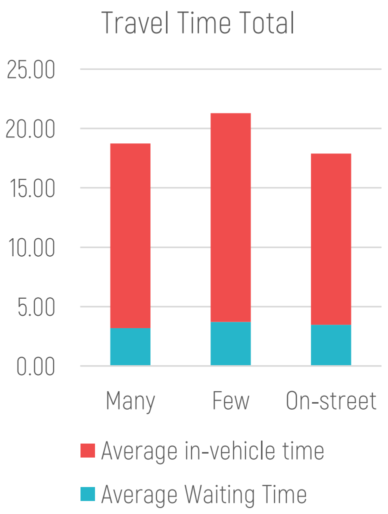


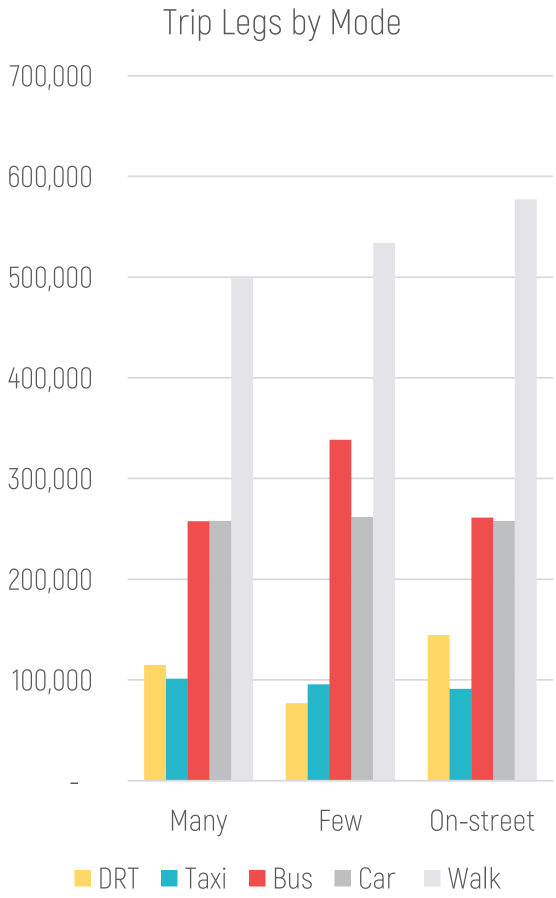
Table 9.11 Distance-based occupancy comparison of all three PUDO models

	Many	Few	On-street
Distance based occupancy (DRT)	6.43	8.67	8.31
Distance based occupancy (DRT+Taxi)	2.73	2.48	3.21

Table 9.12 Comparison of dwell length required at PUDOs

	Many	Few	On-street
Total maximum dwell size (m)	3168	1138	4769
Average maximum dwell size (m)	22.31	27.76	20.38
Average dwell length used over the day (m/day)	0.59	1.08	0.44

Figure 9.28 Comparison of total trip legs by mode for all PUDO strategies



9.3.2 Few PUDOs, few DRT Riders

Fewest DRT trips

Intuitively we can say that DRTs will become less attractive when there are fewer locations available to access them which was confirmed in the simulation as well. The total number of DRT legs is the lowest in *Few* among all models as shown in Figure 9.28, both as an absolute number (almost half of the total DRT trip legs in *On-street* model), and as a percentage of the total legs (6%, compared to 9% and 11% in *Many* and *On-street* respectively). The rejection rate for DRT requests is also high at 23%, as shown in Figure 9.29 (but lower than *Many* at 26%).

Longest walk to transit, wait time, travel time, detours

Providing fewer PUDOs that are placed farther apart leads to longer walking distance to transit. In the simulation with fewer PUDOs, while the highest number of walking trips are made (see Figure 9.28), the average walking time is also the highest (see Table 9.13). Walking long distances can be uncomfortable in Singapore's tropical weather. In addition to the walking time to transit, the waiting time and in-vehicle travel time is also the longest in *Few*, as shown in Figure 9.27. The longer distances between PUDOs leads to the highest detour ratio among all three models (see Table 9.14). Therefore, higher car and taxi use is encouraged.

Highest car and taxi VKT

Private car legs and VKT is highest in *Few* compared to the other two models. Taxi legs are also reasonably high. The most significant change can be seen in bus legs in Figure 9.28, which is dramatically higher in *Few* compared to the rest. Providing fewer PUDOs makes buses very competitive, evident in the visibly high dwelling times of buses in Figure 9.30. Despite the high use of buses, this strategy generates the highest car and taxi VKT and the highest empty VKT by taxis, as shown in Figure 9.31.

Few PUDOs, lower distance-based occupancy overall

Fewer PUDOs also allow better bundling of shared rides. Distance-based DRT occupancy is the highest in the *Few* model. Since the taxi use is very high, the overall distance-based occupancy is the lowest among all three models, as shown in Table 9.11. This low occupancy negates the benefits gained from high bus ridership. If a good pedestrian network is designed to access these few PUDO points, and if the bus service is regular and frequent, this drawback may be overcome. Simulating lowered pedestrian impedance in combination with few PUDOs would be a way to investigate this assertion but is outside the scope of the design experiment framework.

Fewer PUDOs used more efficiently than Many

An interesting result of the *Few* model was the low space requirement for PUDOs. Since there are much fewer PUDO provided low space requirement is expected in terms of the total requirement. *Few* PUDOs were expected to be larger in size than *Many*, since they serve more vehicles per PUDO. However, this was not found to be the case. As shown in Table 9.12, the difference between the average PUDO size in *Many* (22.3 metres) and *Few* (27.8 metres) is not that big. One reason for this result could be that although more vehicles are arriving at a single PUDO in *Few*, they are better spread out through the day, as reflected in the average dwell length for the entire day. The average dwell length per PUDO is almost double in *Few* compared to *Many*. Figure 9.32 spatially shows the maximum dwell length of the PUDO represented by the size of the circle, and the average dwell length of the PUDO, represented by its colour, for *Few* and *Many*.

Few PUDO efficient, but only with improvement in walkability

We can see that with *Few* PUDOs we can minimise the spatial imprint of PUDO infrastructure by using it more efficiently. We can also improve bus ridership and facilitate better bundling of rides for DRT. However, to minimise emissions and improve the level of service for transit, measures must be taken to discourage car use and improve walkability, without which this strategy could even be detrimental to the city.

Figure 9.29 Comparison of total DRT rides and rejections in all three PUDOs

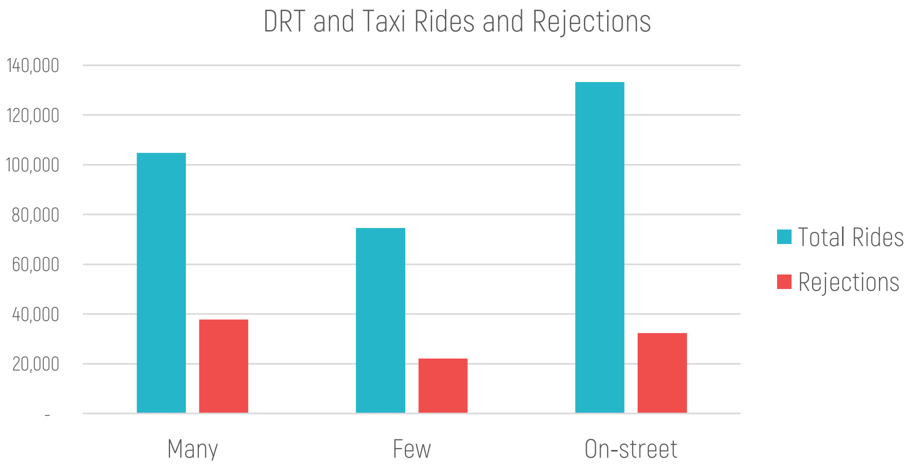


Figure 9.30 Comparison of dwell time at PUDOs for shared modes in PUDO experiment

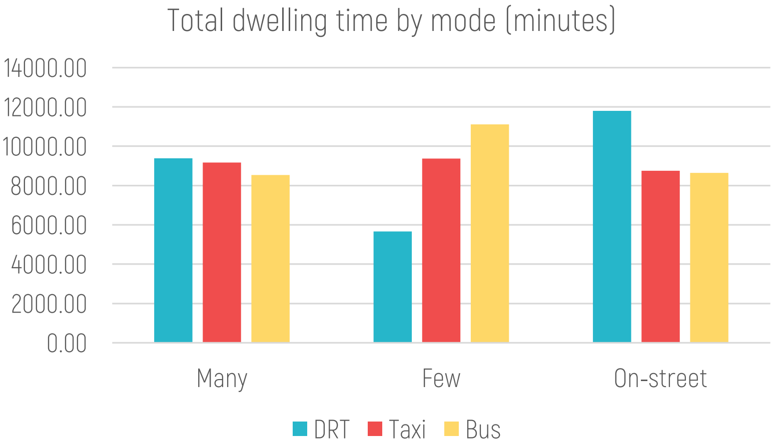


Table 9.13 Comparison of walking time to transit in all three PUDOs

	Many	Few	On-street
Total walking time to transit (hr)	28200	29574	27473
Average walking time to transit (mins)	8.51	8.85	8.00
Median walking time to transit (mins)	5.48	7.23	5.02

Figure 9.31 Comparison of Total VKT generated by private cars, taxi and DRT in all PUDOs

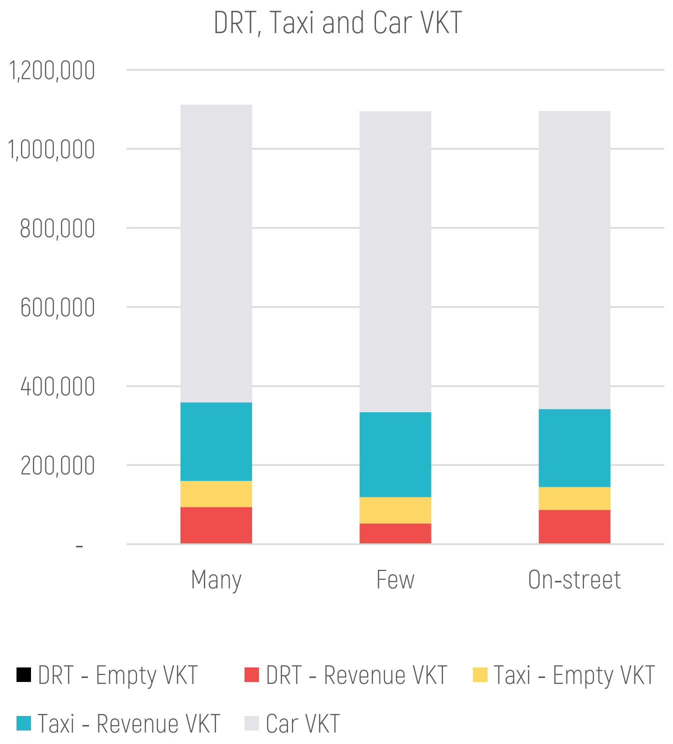
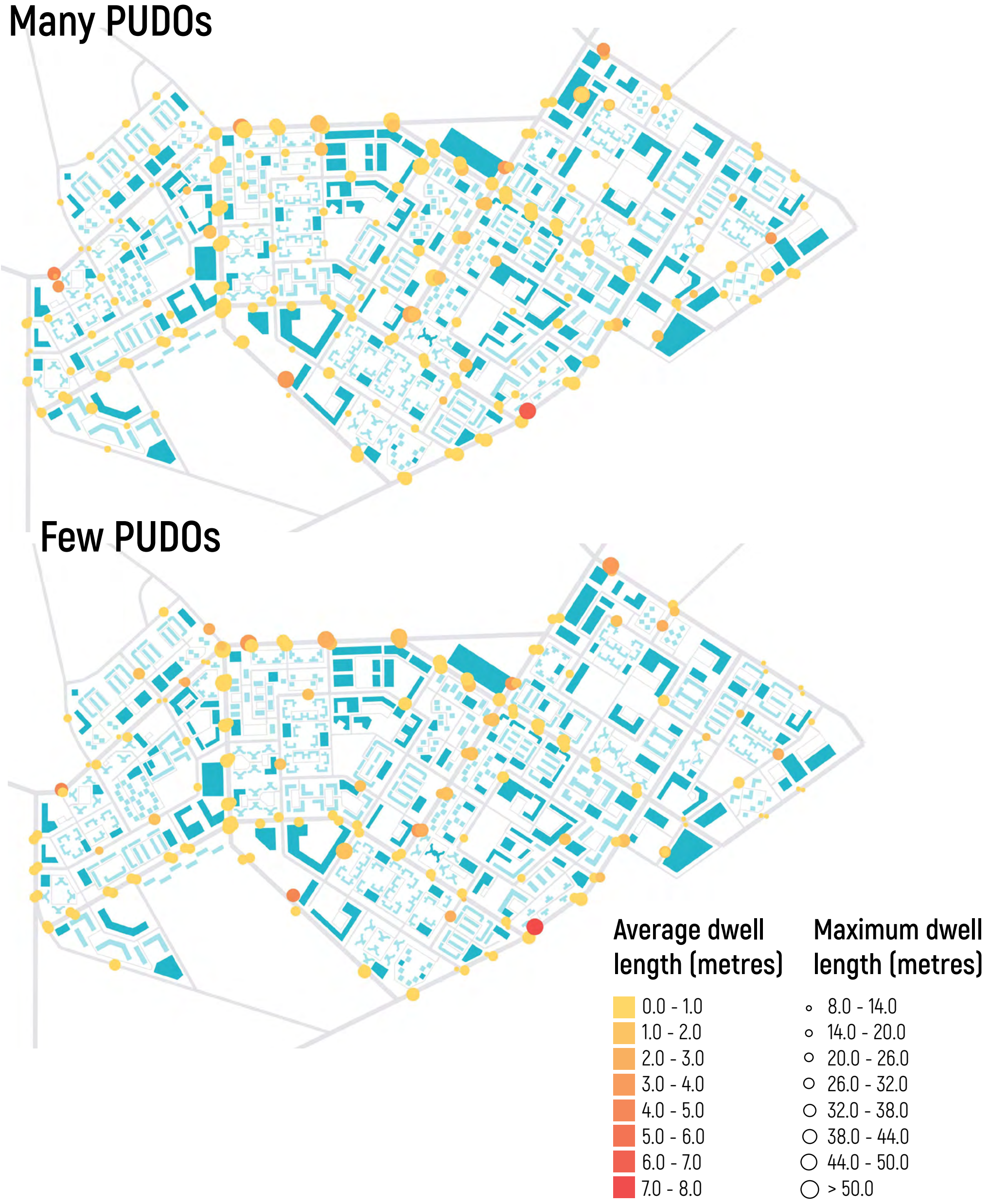


Figure 9.32 Average and maximum dwell lengths by PUDO for both Many and Few models



9.3.3 On-street PUDO as the best of both worlds

On-street PUDO combine benefits of few and many

On-street is an interesting in-between alternative, that provides similar levels of service as *Many*, with fewer VKT generated and better bundling of rides, similar to *Few*. Most DRT rides are served in this model, with fewest rejections at the rate of 20% (see Figure 9.28). The highest number of trip legs for DRT and the lowest for taxi and private car can be seen here (see Figure 9.28). The lowest number of empty VKT is generated in this model, as well (see Figure 9.31). There are several reasons for this.

Why does on-street generate lowest VKT?

First, on-street PUDOs allow better bundling of rides, with the DRT occupancy being only slightly lower than that in Few, as shown in Table 9.11. The better ride bundling may be a result of short walking distance to PUDO, the lowest among the three models, as shown in Table 9.13. Second, since the access area available for the PUDO is more, the waiting time is relatively short. Finally, since the mean distance travelled per ride and the detour ratio is the shortest (see Table 9.14), the in-vehicle travel time is the shortest (see Figure 9.27). A combination of easy access to PUDO for pedestrians and DRT, results in better DRT performance, more walking trips and lower usage of private vehicles (see Figure 9.28).

Trading off space gains for network speed

One expected drawback of the on-street PUDO is the loss in network performance due to a reduction in the street capacity every time a vehicle is performing PUDO activity. The average peak speed of the network, as well as the peak speed to free speed ratio, is the lowest in the *On-street* model, as shown in Table 9.15, although this difference is minimal. Considering the gains made in space use, and the reduction in VKT, the lowered network speed may be a good trade-off.

Table 9.14 Mean distance travelled and detour ratios for all three PUDOs

	Many	Few	On-street
Mean distance travelled/ride (km)	5.70	6.00	5.35
Mean direct distance/ride (km)	2.75	2.85	2.63
Detour Ratio	2.07	2.11	2.04

Table 9.15 Comparison of Network speed in all three PUDO models

	Many	Few	On-street
Avg network freespeed*	42.77	42.77	42.77
Avg Network Peak Speed*	38.98	39.30	37.95
Length wtd Avg off-peak speed*	40.81	40.90	40.24
Avg peak speed/free speed	0.93	0.93	0.92
Avg off-peak speed/free speed	0.97	0.97	0.96

* Average of average speed on all links, weighted by link length

9.3.4 Summary

Temporal use of PUDO space

An interesting outcome of this experiment is how the intensity of usage of a PUDO over the day impacts its area requirement. Temporal variations in the use of space are hardly ever captured through traditional urban design methods. This information can be a significant input in preparing design specifications for PUDOs. For example, consider the scatter plot of maximum dwelling length vs average dwelling length over the day for all PUDOs in the three models, in Figure 9.33. We can see that this is not a linear relation, where larger PUDOs are used more intensively. Some large PUDOs are barely used, probably because they see a lot of traffic during peak hour and remain unused most of the day. How can this information be used in PUDO design?

PUDO design based on temporal variations in use

We can divide the scatter plot into four quadrants, as shown by the red line in Figure 9.33. The points on the bottom left represent smaller PUDO with low usage. This area is busiest for *Many* and *On-street*. The top-right quadrant represents larger PUDOs that are used more often. This section is busiest for *On-street*, indicating that most PUDOs are well used in this strategy. All PUDOs in this quadrant can be related to their geographic location, as shown in Figure 9.32, and further integrated with amenities and retail to maximise the opportunity presented by the high footfall.

Now consider the bottom right quadrant. These are smaller PUDOs with high activity. This quadrant is busiest in Few, indicating a very efficient use of space. Finally, the top-left quadrant represents the most inefficient PUDOs, that remain unused most of the time, but get very busy for a short period. This quadrant is busiest for Many. The size of these PUDOs can be smaller than peak requirement since even if all vehicles conducting pick-up/drop-off activity are not accommodated in the bay, the traffic will only be disrupted for a short period. In this way, individual PUDOs can be identified from the scatter plot to customise the design. A summary of the simulation results for the three PUDO models is shown in Table 9.16.

Figure 9.33 Scatter plot of maximum vs average dwelling lengths at PUDOs over the day

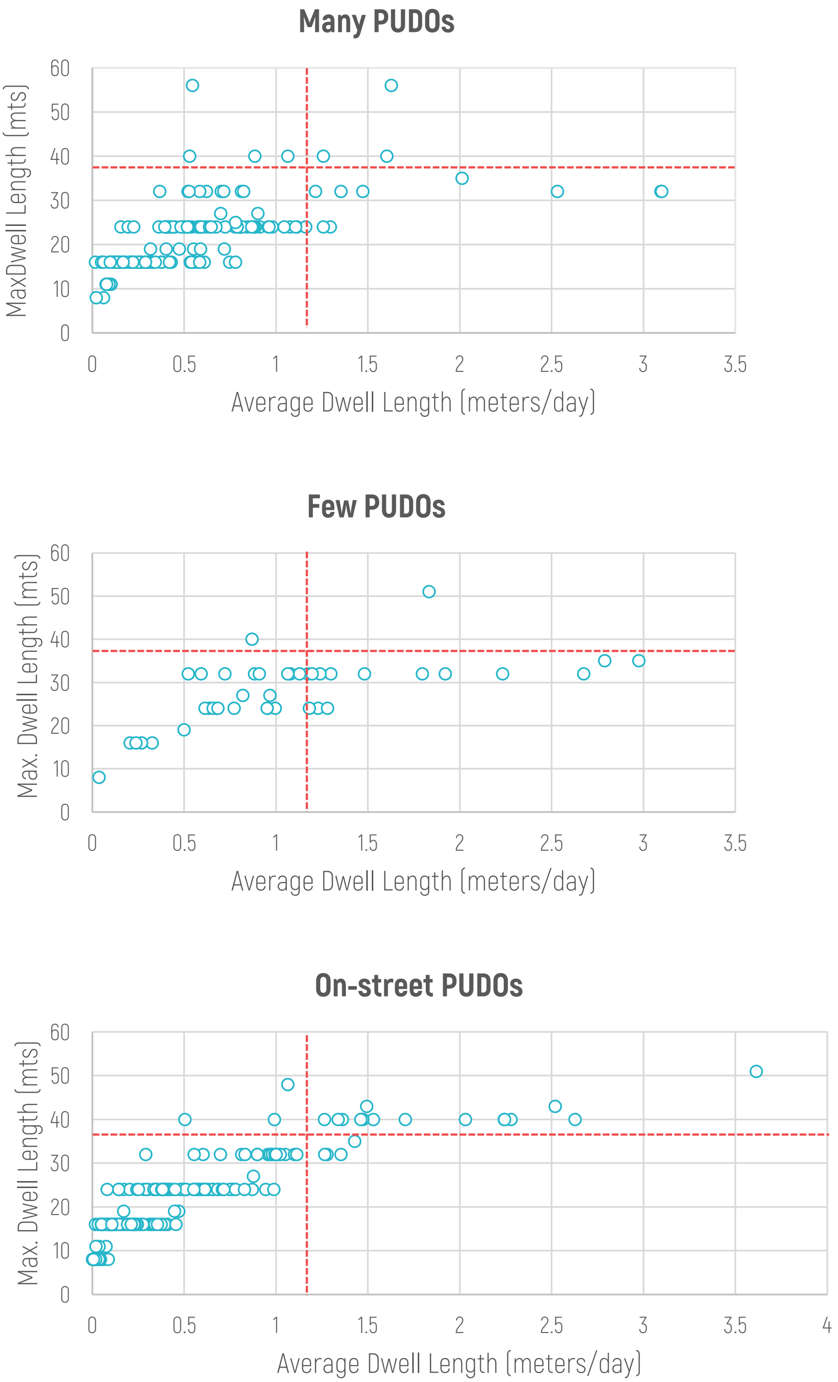


Table 9.16 Results from the PUDO Experiment

	Many	Few	On-Street
Traffic Flow	⬜ Network performance is almost the same as with few PUDOs, and total travel time is moderate.	🟦 Similar network performance as with Many PUDOs, slightly higher peak speed	🟥 Worst network performance (peak speed as a ratio of free speed)
Active Mobility	🟥 Low rates of walking	⬜ Longest walking distance but higher rates of walking than with Many PUDOs	🟦 Highest walking rates and shortest walking time to transit
Transit Access	⬜ Shortest waiting time, medium in-vehicle travel time, but lowest bus use.	⬜ Highest bus usage with few PUDOs, but lowest DRT usage and long wait times	🟦 Short wait times and travel times for DRT. Highest DRT ridership, medium bus ridership.
Traffic Emissions	⬜ Highest VKT generated here, but less empty VKT than in Few	🟥 Lowest overall VKT, but high empty VKT, and highest private car and taxi use	🟦 Lowest empty VKT, low car and taxi use
Space & Space Use	🟥 Large space requirement for PUDOs	⬜ Least PUDO space required	🟦 Lowest amount of space required since no special infrastructure needed.

🟦 Highest Score

🟥 Lowest Score

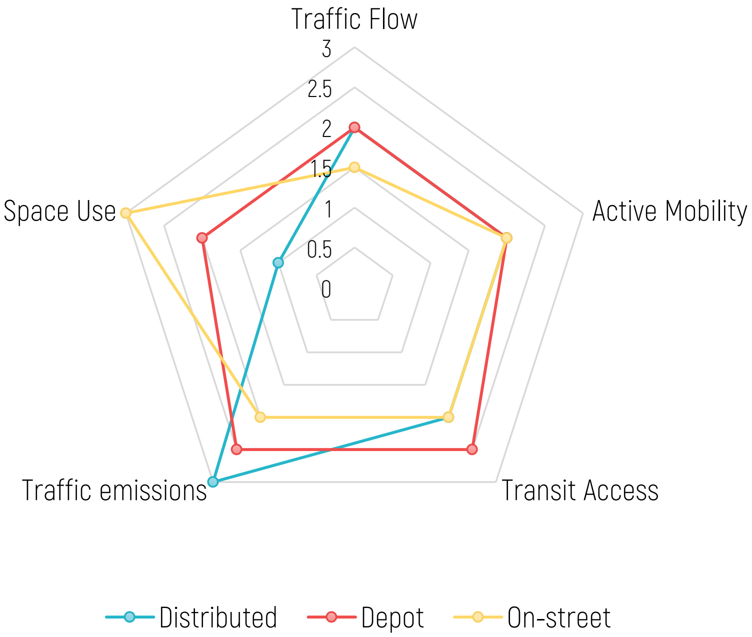
⬜ Medium Score

9.4 Which parking strategy is the most efficient?

A combination of depot and on-street performs best

Both shared *Depot* and *On-street* parking strategies perform well here, as shown in Figure 9.34. In reality, probably a combination of both will be required depending on the vehicle type and the street type. Two main conclusions can be drawn from this experiment. First, it is clear that fixed purpose-built parking structures are inefficient, and will become redundant with an increase in vehicle sharing. Second, both the total parking spaces required, as well as parked time, will reduce. Therefore, more dynamic parking spaces on-street (or in lots) may be a more prudent choice in the future. We will now discuss these conclusions in detail.

Figure 9.34 Comparison of performance of three Parking types



9.4.1 Fewer parking facilities need fewer parking spaces

More parking options means more parking spaces required

When more parking options are available, more parking spaces are required overall, as shown in Table 9.17. In the *distributed* model, parking spaces amounting to almost 150% of the total vehicle stock is needed at the maximum. However, when DRT vehicles and taxis are only allowed to park in three large shared depots at the periphery of the site, almost the same number of parking spaces are needed as the total vehicle stock. The minimum number of vehicles parked in all lots through the day is almost the same for both *distributed* and *depot* parking strategies, at about 30% of the total vehicle stock. With *distributed* parking, different lots experience their peak at different times, leading to an increase in demand overall.

Distributed parking

There are 35 parking lots in the *Distributed* strategy, the largest one requiring 132 spaces at the maximum. However, on average, only seven spaces are used most of the time, which suggests a gross under-utilisation of space in the *Distributed* parking strategy. Figure 9.35 shows the distribution of parking in all three models, coloured by maximum occupancy.

Trade-off space with emissions in distributed

With *Distributed* parking strategy, we trade-off higher space requirement with fewer emissions. Vehicles have to drive farther to and from the shared *depots* generating empty VKT. In the simulation, *Depot* has the highest empty VKT, nearly 20% of all VKT driven, as shown in Figure 9.36. Depots also have the highest distance-based occupancy and highest dwelling time for DRT (see Figure 9.37), indicating more intensive use of shared DRT vehicles. Vehicles are on the road longer with *Depots* as compared to *Distributed* parking, which may be why DRTs are used more intensively. The waiting time for DRT, average walking time, in-vehicle travel time, and detour ratio are not significantly impacted whether *Distributed* or *Depot* parking is provided.

Table 9.17 Maximum and minimum number of parking spaces used in each parking model

	Distributed	**Depots**	**On-street**
Maximum total Parking Spaces	1274	928	325
Minimum spaces used over the day	255.7	245.2	108.0
Maximum spaces as a % of the vehicle stock	148%	108%	38%

Figure 9.36 Comparison of total empty and revenue VKT driven by DRT, taxi and cars

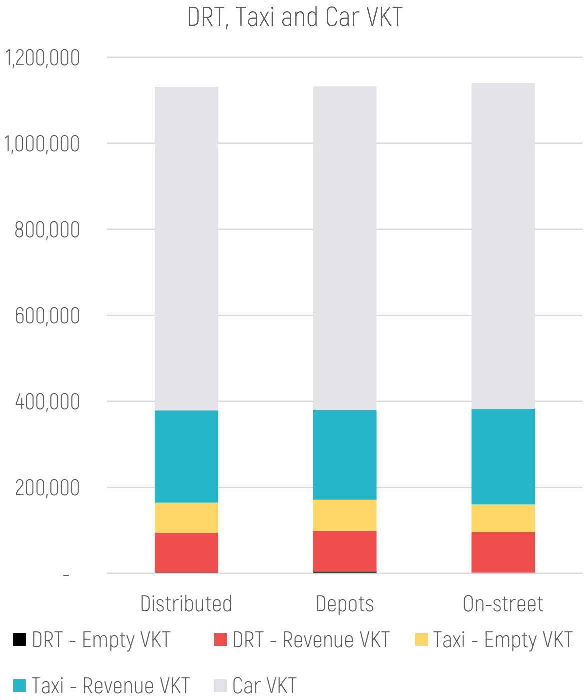
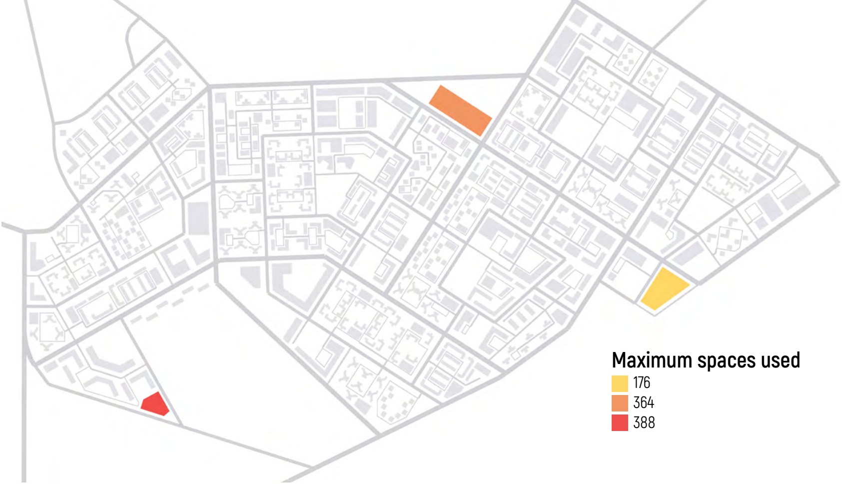


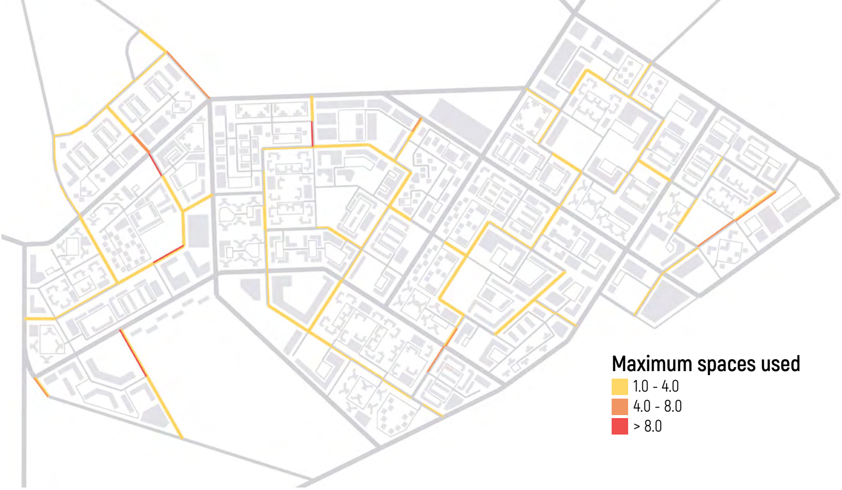
Figure 9.35 Maximum vehicles parked in every lot for the three Parking strategies

3.1 Distributed

3.2 Depots



3.3 On-street



9.4.2 On-street parking for a shared vehicle driven future

Least space required, more VKT generated

On-street parking requires the least amount of street space, only about 38% of the vehicle stock at the maximum. The vehicles are also parked for very short periods, as is evident from the very low minimum parking requirement (almost half of the other two models, as shown in Table 9.17). Vehicles are barely parked and move around a lot in this model, probably cruising for parking, generating the highest overall VKT (and Taxi and DRT VKT). The high taxi usage is also evident in the high dwell times for taxi in Figure 9.37. At the same time, fewest empty VKT is generated here, which means the vehicles are not cruising empty. This finding needs to be investigated further.

Is on-street parking causing any congestion?

Another unexpected result in *On-street* is the increase in car VKT, which is the highest in this model. The network capacity is slightly reduced, which may generate congestion, encouraging people to switch to private cars instead of shared vehicles. In the simulation, we see a slight drop in network performance, as shown in Table 9.18. However, the difference between peak speed to free speed ratio in all three models is so small that it seems unlikely that on-street parking causes any real congestion. The increase in car VKT needs to be investigated further.

More time required for PUDO activity on the street than for parking

On-street parking does not have any significant impact on network performance. If we compare the network peak speed for on-street PUDO (see Table 9.15) with that in on-street parking, we find that it is much lower in the former than in the latter. We can interpret this result as indicating that the lanes are occupied much longer for PUDO activity than they are for parking. The reduced amount of parking time suggests a need to shift from static parking structures to dynamic parking areas.

Figure 9.37 Comparison of total dwelling time at PUDOs in all three parking models

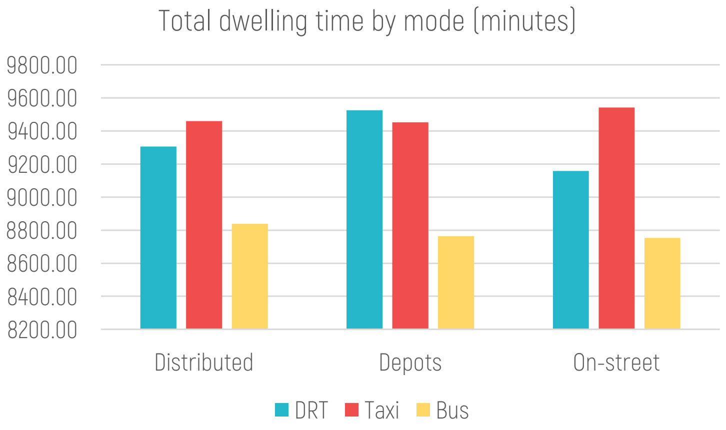


Table 9.18 Comparison of network speed in the three parking models

	Distributed	Depots	On-street
Avg network freespeed*	42.77	42.77	42.77
Avg Network Peak Speed*	39.12	39.16	39.01
Length wtd Avg off-peak speed*	40.77	40.79	40.78
Avg peak speed/free speed	0.93	0.93	0.92
Avg off-peak speed/free speed	0.97	0.97	0.97

* Average of average speed on all links, weighted by link length

9.4.3 Summary

We find some complex dynamics emerging in the parking experiment regarding mode choice and VKT generated, which are difficult to explain at this stage. The most favourable parking strategy is depot or on-street parking, depending on how congested the existing network is. A summary of the simulation results for the three network models is discussed in Table 9.19.

Table 9.19 Summary of results from the Parking Experiment

	Distributed	Depots	On-Street
Traffic Flow	⬜ Similar peak speed and peak speed ratio as with depots	⬜ Similar peak speed and peak speed ratio as with distributed parking. In-vehicle travel time is slightly shorter	🟥 The network is slower, but in-vehicle travel time is medium
Active Mobility	⬜ Similar walk time and walking trips	⬜ Similar walk time and walking trips	⬜ Similar walk time and walking trips
Transit Access	⬜ Slightly higher Public transit use	🟦 Slightly higher average waiting time, but the highest overall occupancy. Higher DRT use	⬜ Higher car and taxi use but short wait time and travel time.
Traffic Emissions	🟦 Lowest overall VKT, and car VKT	⬜ Highest empty VKT	🟥 Minimum detour ratio for DRT. High private car legs and VKT. High taxi use as well. Highest overall VKT
Space & Space Use	🟥 Most amount of space needed	⬜ Less space needed	🟦 No specific infrastructure needed

🟦 Highest Score

🟥 Lowest Score

⬜ Medium Score

9.5 Which intersection type performs best?

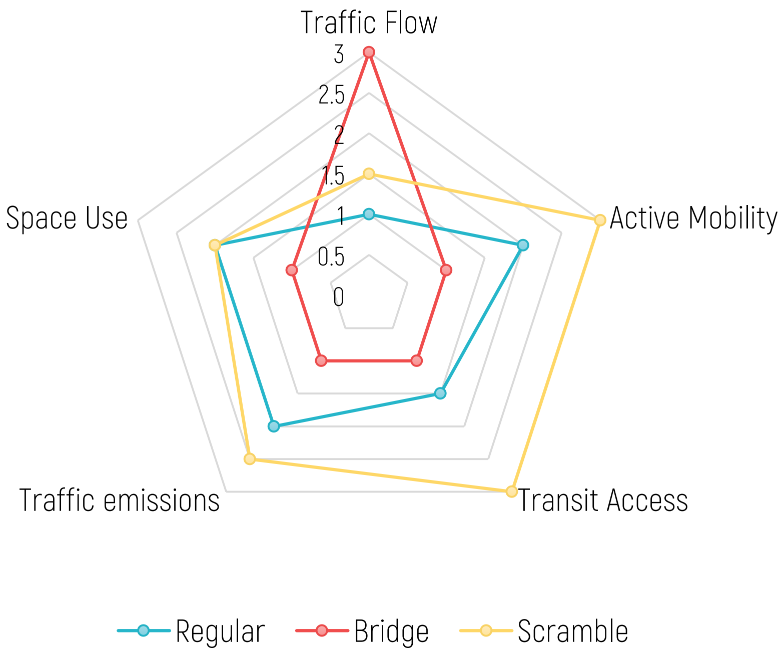
Scramble performs best

Scramble is an appropriate choice for intersection due to its benefits for the overall system, as shown in Figure 9.38. However, a bridge intersection may need to be implemented in places where high network performance is required. In either case, the intersection of the future will not be a regular signalised intersection, but some sort of slot-based system. Given this, we need to decide if platoons of AVs at SI stop at regular intervals for pedestrians/cyclists, or if their movement paths are completely separated through grade. In the former case, pedestrians perform better, and in the latter vehicular traffic.

Two conclusions

Two main conclusions can be drawn from this experiment. First, the combination of improvements in network efficiency, reduction in taxi price due to automation, and addition of impedances for pedestrians, leads to high taxi VKT and empty VKT. Ridership of all shared modes goes down despite better network performance. This effect was also evident in the Network experiment in the *Grid* model. Second, even slight improvement in walkability can dramatically improve the usage of shared modes, reducing overall VKT significantly. A similar effect was seen in the *Superblock* model in the Network experiment. We will now discuss these conclusions in detail.

Figure 9.38 Comparison of performance of three Intersection types



9.5.1 Faster network equals higher VKT

Taxis become more attractive in bridge

In the *Bridge* model, as the intersection capacity doubles, the mean travel time and waiting time decline significantly, as shown in Figure 9.39. The low travel time leads to an upsurge in taxi use, as shown in the distribution of trip legs by mode in Figure 9.40. High taxi use is accompanied by a decrease in transit ridership as well as private car usage. The higher sensitivity of taxi pricing to time and congestion versus higher sensitivity of private cars to distance travelled leads to a decline in private car use. For very short trips, taxis can be even more affordable than private cars, as discussed in the Network experiment. Thakur et al. (2016) also support this argument that ride-sourced AV will be cheaper than a private car, but they assume this would lead to higher transit use. In this model, despite faster travel times, buses and DRT are mostly empty, as reflected in the comparison of dwelling time by mode in Figure 9.41. Notice the sharp rise in taxi dwelling time in the same figure.

High VKT and empty VKT

The increase in taxi ridership results in the generation of the highest number of VKT, almost an 8-9% increase from the other models, as shown in Figure 9.42. Highest total empty VKT is also generated by taxis and DRT in this model, almost double that in *Regular* and *Scramble*. Almost 30% of all the distance driven by taxis in *Bridge* is empty VKT. The presence of pedestrian bridges at every intersection increases the walking time to transit, in turn reducing the total walking trips, as can be seen in Figure 9.40. Even though waiting time and in-vehicle travel time is the lowest for *Bridge*, the long walking time discourages pedestrians from accessing PUDOs and bus stops. A suitable alternative to taxi must be provided for short single person trip to overcome the shortcomings of *Bridge*. Well-connected cycling and PMD network is essential for this, but challenging to implement with bridges at intersections.

Figure 9.39 Mean travel time and waiting time in all three intersection types

Figure 9.40 Comparison of trip legs by mode for three types of intersections

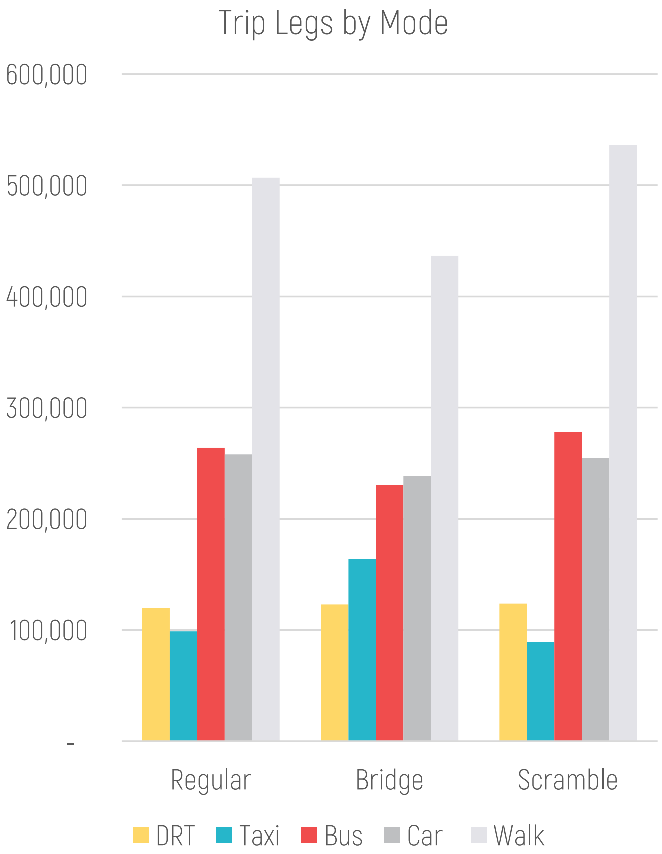


Figure 9.41 Comparison of dwelling time for modes in the three intersection types

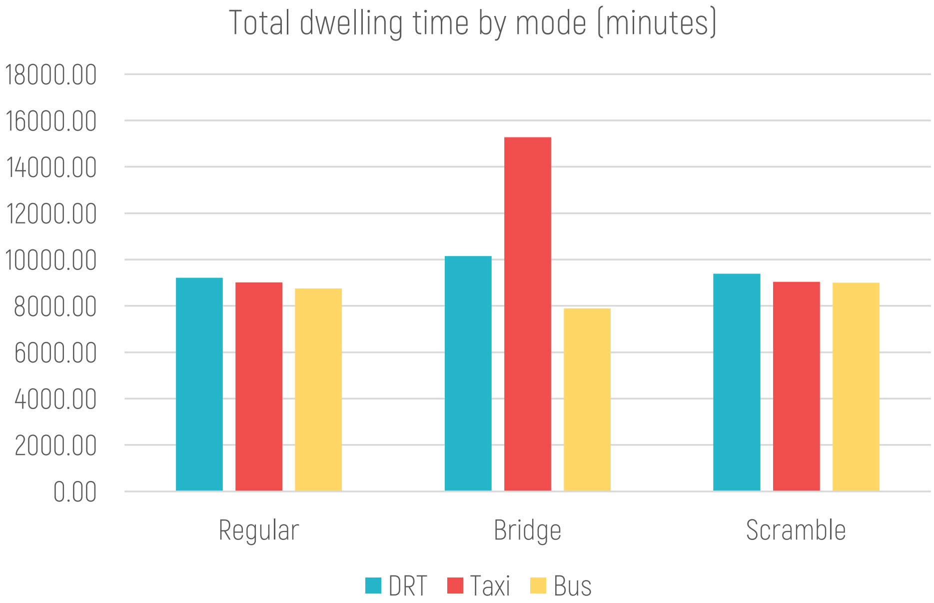
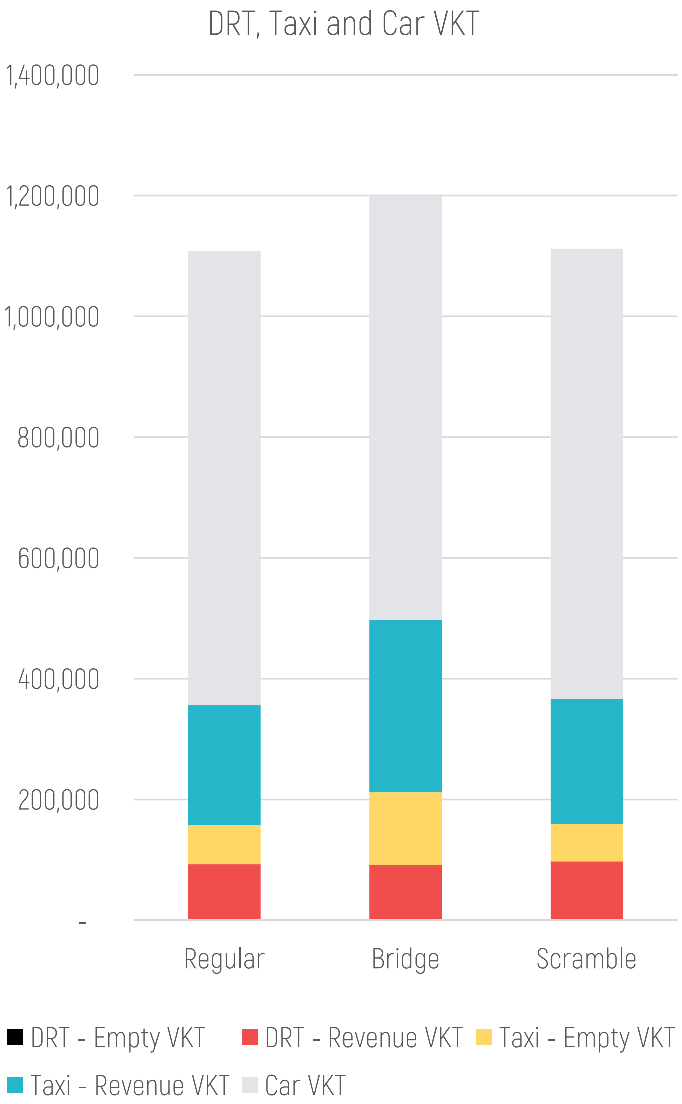


Figure 9.42 VKT by DRT, Taxi and Cars in the three intersection models.



9.5.2 A little bit for walkability goes a long way for all

Improvements in walkability have a cascading effect

In the *Scramble* model, a slight improvement in walking time is assumed, to begin with, accompanied by a slight reduction in intersection capacity. This small change in walkability has a cascading effect on all shared modes. *Scramble* has the highest DRT occupancy rates (see Table 9.20), the highest number of DRT and bus trip legs (Figure 9.40) and the highest dwell time for buses (Figure 9.41). The taxi trips are also the fewest in this model, with the fewest empty VKT. Due to the short walk time, the number of walking trip legs are also the highest.

Higher waiting and travel time

While we gain high ridership of shared modes and low empty VKT in *Scramble*, we get slightly higher waiting time and in-vehicle travel time (Figure 9.39) as a trade-off. The network is not as heavily congested in *Scramble* as expected. The average network speed during peak hour in *Scramble* is almost the same as that in *Regular*, and even slightly better during off-peak hours. The network performance can be spatially analysed in Figure 9.43. *Bridge* is much faster than the rest, but there is not much difference between *Regular* and *Scramble*.

9.5.3 Summary

It is important to acknowledge that the dynamics of the simulation in this experiment are the crudest. An intersection experiment specifically requires a more fine-grained understanding of traffic dynamics and pedestrian interactions. For example, the performance of a scramble crossing varies greatly depending on the amount of vehicular or pedestrian traffic. Here we assume a uniform reduction in intersection capacity when, in some cases, it has been seen to increase intersection capacity based on local conditions (Tự and Sano, 2014). Similarly, we assume a high impedance for pedestrians in *bridge*, when in fact bridges can be designed in many ways to reduce pedestrian impedance, such as using elevators or sinking the road at intersections. A finer-grained agent-based simulation is required for a more nuanced understanding of the dynamics of the intersection in this experiment. A summary of the simulation results for the three network models is discussed in Table 9.21.

Table 9.20 Comparison of occupancy rates of DRT and Taxis for all three intersection types

	Regular	Bridge	Scramble
Distance based occupancy (DRT)	6.80	5.96	6.71
Distance based occupancy (DRT+Taxi)	2.83	2.19	2.81

Table 9.21 Summary of results from the Intersection Experiment

		Regular		Bridge		Scramble
Traffic Flow	🟥	Lowest peak speed	🟦	Best peak speed and network performance	⬜	Slight improvement in peak speed
Active Mobility	⬜	High walking time but medium walking trips	🟥	High walking time and least walking trips	🟦	Most walking trips, shortest walking time
Transit Access	⬜	Highest private car use, lowest DRT use, but medium bus use	🟥	Highest taxi use, lowest bus use	🟦	Highest bus use, DRT trips
Traffic Emissions	⬜	Lowest overall VKT, medium empty VKT	🟥	Highest overall VKT, highest empty VKT	🟦	Lowest empty VKT, medium total VKT.
Space & Space Use	⬜	Similar amount of space required as scramble	🟥	A lot of additional infrastructure required. Highest amount of PUDO space required.	⬜	Similar amount of space required as regular

🟦 Highest Score

🟥 Lowest Score

⬜ Medium Score

9.6 Recommendations

Based on the results of the simulations in the four design experiments, specific recommendations can be made, regarding the design of the network, pick-up/drop-off points, parking infrastructure and intersections, in response to the technological shift.

Network design

1. A connected network topology is generally beneficial but could be detrimental without an appropriate pricing strategy to discourage taxi use accompanied by improvements in the active mobility network.

2. Lowering the overall network speed could lead to improvements in travel time as rates of ridesharing grow.

3. Last-mile connectivity is difficult to solve for current HDB New Town networks through DRT deployment alone. Enhancing pedestrian connectivity is vital to address this issue.

PUDO design

1. Over-provision of PUDOs may result in better service level but can generate high VKT. It is prudent to do a time-based simulation analysis to understand the optimal number and location for PUDOs. In this case, 18 PUDOs per neighbourhood results in high VKT, while 6 PUDO per neighbourhood reduces DRT ridership.

2. We can see that with the provision of fewer PUDOs, we can minimise the spatial imprint of PUDO infrastructure by using it more efficiently. We can also improve bus ridership and facilitate better bundling of rides for DRT. However, to minimise emissions and improve the level of service for transit, measures must be taken to discourage car use and improve walkability, without which this strategy could have counter effects.

3. Wherever possible, on-street PUDO is preferred for the most efficient use of space and ease of access.

Parking Infrastructure

1. Fewer shared parking facilities are preferred over many smaller facility-specific parking structures. The gains in space efficiency, in this case, are quite significant compared to the minor increase in VKT.

2. Wherever possible, on-street parking must be provided. Considering growing use of shared vehicles, not only do we require least parking space in this strategy, but the vehicles are also parked for the smallest amount of time. Therefore, the losses in network performance are negligible.

Intersection type

1. Creating grade separation between pedestrians and AVs improves network performance, but also generates more VKT. A suitable alternative for short single person trips must be provided to avoid this. Well-connected cycling and PMD network is essential for this but can be challenging to implement with grade separation.

2. A slight reduction in intersection capacity can even increase overall network speed when accompanied by improvements in pedestrian infrastructure. Wherever possible, a scramble crossing must be implemented to achieve this.

10 Towards the Post-Road City

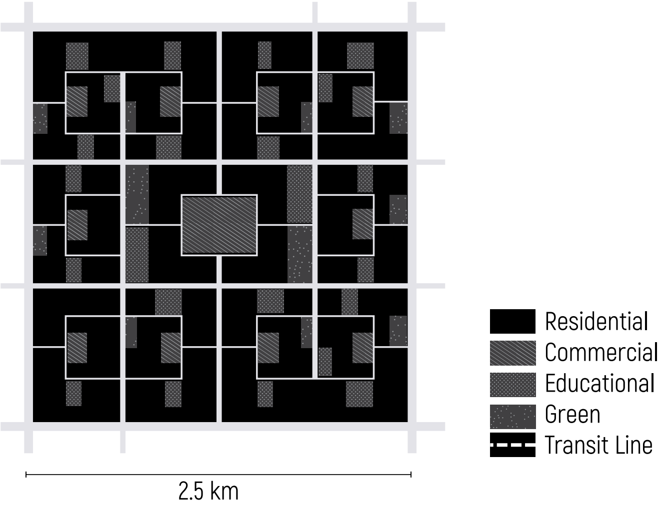
We will now address the question we began this empirical study with, regarding how the prevailing New Town model can be modified, or wholly reimagined, in the context of the technological shift in transportation. The urban design response is delineated through three stages – retrofitting the New Town in the *Short-term* (next five years), modifying it further in the *Mid-term* (next ten years), to finally converge at the 'Post-Road City' in the *Long term* (twenty years).

In the previous chapter, four questions, regarding the design of the network, PUDO, parking and intersections, were investigated in detail through design experiments. Recommendations for the design of these specific elements were derived from the experiment results, which will now be used to put together a holistic urban design response to the technological shift in transportation, in the context of the Singapore New Town. Our goal to wean off the current patterns of automobility, towards new mobility behaviours enabled by the technological shift. Therefore, the response also emerges in stages, from retrofitting interventions to a more radical transformation in the long term.

Each stage is laid out in the form of a narrative which begins with the description of the state of technological development, public acceptance and uptake of technology assumed for that point in time. Key challenges and urban design goals are identified for each stage, followed by specific design interventions to respond to them. It must be noted that this development path is entirely based on the assumptions regarding the state of technological development and its market penetration, which can be highly precarious. This issue has been dealt with in greater detail in the concluding chapter.

10.1 Short-term: Retrofitting the New Town for the next five years

Figure 10.1 The New Town Structural Model



2 Short term design challenges

We begin with the existing New Town Structural model that was used as a basis to construct the base model, as shown in Figure 10.1, to investigate how it can be retrofitted in the short term. Two primary design challenges need to be addressed in the short term – the poor first/last mile connectivity and infrastructure redundancy.

Vehicular mix

We can expect Level 4 automation in some commercially available vehicles in the short term, but the streets would still be dominated by human-driven vehicles. When automated vehicles are only partially deployed, they are not expected to have any significant impact on vehicle ownership rates, as demonstrated by a study on the impacts Automated Mobility on Demand (AMoD) deployment in New Towns. This study suggests that with partial deployment of AMoD, overall private vehicle ownership rates and residential density remains almost the same as in baseline (Meng et al., 2019).

Type of DRT deployed

Automated DRTs can be deployed as an additional mode of public transit in New Towns in the short term. These vehicles should initially be allowed to operate only inside the New Town, where their access and egress can be controlled. The selected New Town can be fitted with sensors, signage and other facilities that are needed to implement a public DRT system. It is suggested to deploy larger 10-20 seater DRT vehicles, to begin with, based on the findings from the initial iterations of the Network experiment. Large-sized DRT vehicles would only ply on road types 1-3, based on the road types described in Table 8.4, so as not to disrupt quieter residential areas and to avoid making longer detours.

Possibility of a rise in VKT in the short term

In the near term, we need to make sure that the conveniences afforded by the technological shift, and the impedances offered by the existing urban context, do not increase overall VKT and transport-related emissions. Privately owned vehicles may become even more attractive with automation, and end up cruising empty to search for parking or to perform additional tasks. Since automation impacts the value of in-vehicle travel time, owners of private AVs may even tolerate longer travel times, increasing travel distances. At the same time, if taxi and ride-hailing services also switch to a fleet of automated vehicles, their prices would drop significantly (Bösch et al., 2018a). Consequently, transit ridership would be severely impacted. Due to a combination of these effects, we can expect a rise in VKT.

Improvements needed in transit service and access

To reign in the threat of a rise in VKT, improvements need to be made in public transit service and access. In the Network experiment, buses proved to be the best option among shared modes to serve the disconnected *loops* network. However, the longer average walking distance to transit made buses less attractive and, when possible, travellers chose to use their private car. It follows that to pursue a 'car-lite' future as envisioned in Singapore's masterplan (Urban Redevelopment Authority, 2019), improvements in both transit service as well as transit access are crucial.

Improving transit service

One of the strategies to improve transit service could be to implement 'bus-only' lanes on all bus routes. These bus lanes could be shared by the large DRT vehicles, and fitted with the infrastructure required for level 4 automation. A buffer can be created between the automated bus + DRT lane and the rest of the traffic. Figure 10.2 shows in blue how the existing type 2 roads can be modified by providing a designated buffered lane for buses and DRT. Dedicated transit lanes would make shared modes slightly faster than private modes. Note that no specific intervention is made to slow down other modes intentionally. Existing road widths and sidewalks are maintained.

Improving pedestrian infrastructure to improve transit access

A comprehensive redesign of the pedestrian network must be undertaken to improve access to transit. While vehicular traffic is directed through a hierarchical less connected network, this does not have to be the case for pedestrians. Wherever possible, the shortest path to destinations should be enhanced through design. Legibility of the network should also be given special attention since pedestrians may need to follow a completely different route from vehicular traffic, which is currently better defined. Gradually, this network should be supplemented with an equally well-connected bicycle/personal mobility device (PMD) infrastructure, as shown in yellow in Figure 10.3. All smaller crossings on road types 4-6 can be transformed into scramble crossings to reduce walking distances.

Figure 10.2 A section through road type 2 modified for the short term
Note: Road type 2 from the base model is retrofitted to include a bus-only lane with buffer. Key plan at the bottom left shows the location of the bus lanes on the structural plan.

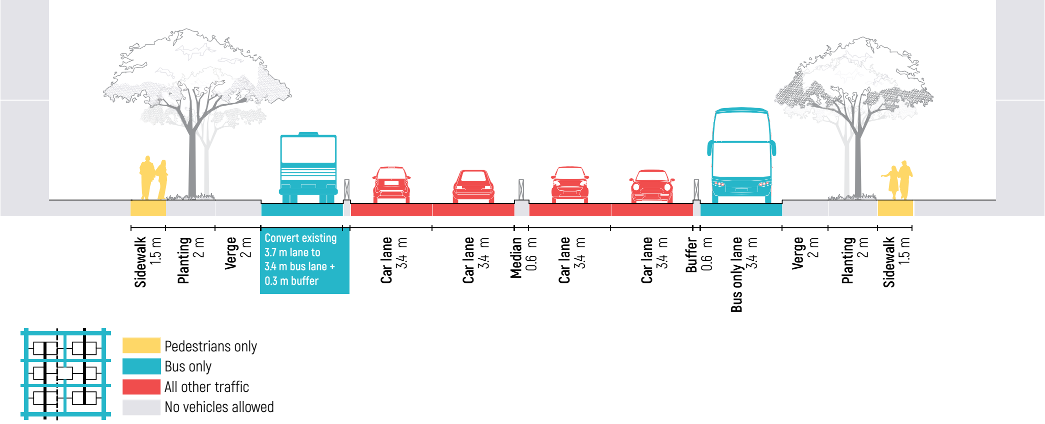
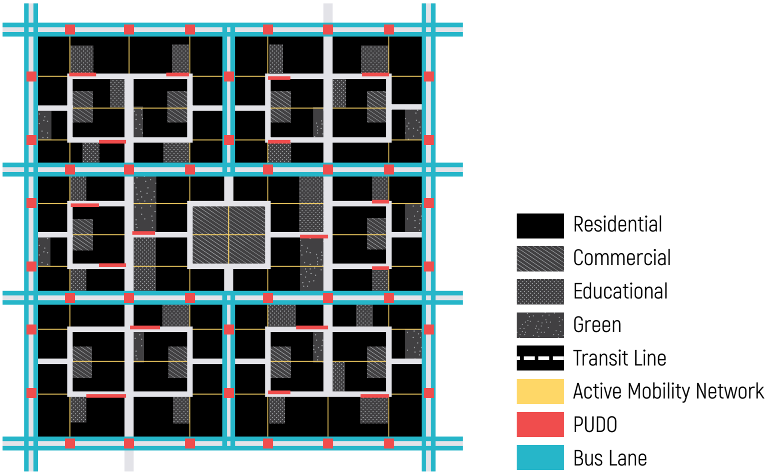


Figure 10.3 Diagram showing some short interventions to retrofit the New Town structural model
Note: In the short term bus lanes and on-street PUDOs are added, and the pedestrian network is improved.



Provide a combination of few bays and on-street PUDOs

Another way to improve access to transit is to provide on-street PUDO, as seen in the PUDO experiment. For the *loop* network, *on-street* PUDO allows us to achieve maximum DRT ridership and lowest car use but results in a slight reduction in network performance. In the short term, users should only access DRT at existing bus stops and taxi bays on faster roads with high traffic volumes (type 1 and 2). However, on-street pick-up and drop-off can be allowed on road type 3 in the leftmost lane, depending on the local traffic conditions. Figure 10.3 conceptually shows a combination of bus stops along bus lanes and small portions of type 3 road being used for PUDO activity in red. Alternatively, a new PUDO bay can be provided.

Deciding between bays and on-street PUDO

When deciding whether or not to provide new PUDO bays, it is essential to consider if it might become redundant in the future. Most simulations reviewed so far show that vehicular traffic is expected to reduce with automation and greater vehicle sharing. Consequently, reducing road space provision is one of the most common responses to the technological shift. Given the benefits of on-street PUDO in improving access to transit and bundling of shared rides, the small reduction in network performance in the short term is a reasonable trade-off. It would be prudent to run a simulation and understand the usage of the PUDOs, as discussed in section 9.3.4. For example, PUDOs in the bottom left quadrant could easily be serviced on-street, but those in the top right may require a bay.

Create an inventory of parking usage

In addition to PUDO infrastructure, redundancy of parking infrastructure is also a serious concern in the short term. A comprehensive review of the *temporal* use of existing parking structures should be made to redefine parking requirements and identify structures that are presently underused. On-street parking on smaller inner roads where possible (after accounting for space required for emergency vehicles) can compensate for the removal of underused parking structures. In neighbourhoods where the deployment of DRT is planned, parking minimums should be abolished, and parking maximums (Manville and Shoup, 2005) can be considered instead. Large DRT vehicles can be allowed to park in bus depots in the short term, by expanding the existing infrastructure.

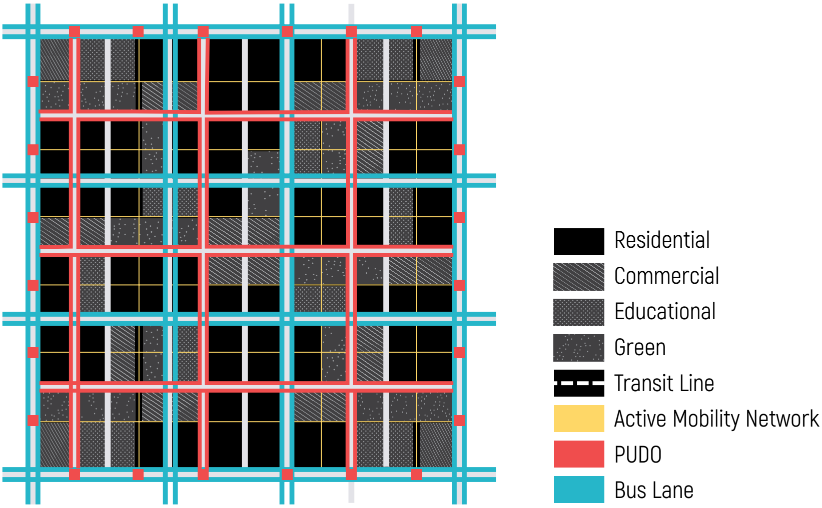
Summary

To summarise, in the short term we need to think about redundancy in any new transport infrastructure being planned while strengthening public transit, both in terms of service and access. A piecemeal implementation of DRT in restricted areas is suggested, with the implementation of buffered bus + DRT lanes and improvements in pedestrian infrastructure, as shown in the retrofitted structural model in Figure 10.3. Building new PUDO bays and parking structures is discouraged as much as possible. The technological shift will not visibly make an impact on urban form at this stage, but these measures will act as buildings blocks to achieve our long term vision of reducing automobile dependency, transport-related emissions and improving active mobility and public space use.

10.2 Mid-term: Making structural changes for the next ten years

Figure 10.4 Diagram showing mid-term interventions to modify the New Town structural model

Note: A more connected typology is created, and more on-street PUDOs are added.improved.



State of technological development and challenges for the mid-term

After the initial introductory phase, vehicle sharing and DRT usage are expected to pick up in the mid-term, especially with improvements in automation technology. We can expect ride-hailing and taxi operators to have mostly transitioned to a driverless fleet with level 4 automation. Consequently, we can then expect a decline in private car ownership, as demonstrated in the study by Meng et al. (2019). Ride-sharing must be supported through design and policy while making sure that public transit ridership is not affected by cheaper taxi service, leading to an increase in VKT. Our goal in the mid-term would be to maximise ridership of shared vehicles and promote them as a complement to public transit. A modified structural model for the New Town is proposed to achieve this goal, as shown in Figure 10.4.

Create a more connected network topology

A structural change is made to the network topology in the mid-term, as shown in Figure 10.4. A well-connected network topology results in high vehicle occupancy rates and smaller detour ratio, as seen in the comparison between *grid* and *loops* in the Network experiment. The dominant *loops* topology in New Towns needs to be modified to make it more integrated and connected, to support shared DRT rides. In addition to the larger DRT vehicles, more agile six-seater vehicles can be deployed in such a connected network which can even be allowed on narrower road types 4-6. Creating more diversity in fleet type provides more options and flexibility to travellers as well.

More connected does not mean more sharing

A connected network topology alone does not guarantee more shared rides. In the Network experiment, despite high DRT occupancy rates, the overall occupancy per vehicle was the lowest in the *grid*, and the overall VKT generated was the highest. The main reason for this was the high taxi use in *grid*. When driver costs are eliminated, taxi becomes much cheaper (Thakur et al., 2016), and with shorter detours and faster travel time enabled by connected network topology, it can be even cheaper and more attractive than private cars. As a result, despite better ride bundling and connections, the reduction in VKT is cancelled out by the increased taxi use. Two types of measures can be taken to counter this effect – by limiting vehicle types allowed on certain streets or by limiting vehicle speeds allowed on certain streets.

Restricting the use of link by mode

By strategically restricting the use of the street by specific modes only, we can improve service levels for shared modes (and hinder other modes). Connected vehicles provide a way of enforcing this policy effectively through geo-fencing. Only DRT, buses, pedestrians and cyclists can be allowed on some ‘connection links’, while private taxis and cars would be required to make long detours. A similar strategy is employed in the Barcelona superblock where private vehicles are not allowed to pass through, and can only enter and exit the block on the same road, as shown in Figure 10.5. The disenfranchising of one user group in the short term for the benefit of all in the long term, through improvements in the environment or quality of life, can lead to political struggles that can jeopardise such a project, as seen in the case of Barcelona (Zografos et al., 2020). Political barriers can make such implementations challenging.

Reducing speed for all modes

Another measure to discourage private taxi use is to reduce the maximum allowable speed on some links in the network for *all* modes. For example, the speed limit on residential roads inside a neighbourhood could be restricted to 25 km/hr, as shown in Figure 10.6, while the wider outer roads can be allowed to maintain high speeds (possibly higher than current standards in buffered bus lanes). The notion of deliberately ‘slowing down’ traffic may also initially be met with some resistance, as with the previous strategy. However, there are plenty of arguments to be found for reducing allowable traffic speeds in transport planning literature (Ewing and Dumbaugh, 2009; Litman, 1999).

Benefits of traffic calming in transport planning literature

Design and policy measures to deliberately slow traffic down are classified under the broad umbrella of ‘traffic calming’ in transport planning literature (Berthod and Leclerc, 2013; Brindle, 1997; De Wit and Talens, 1999; Ewing, 2008). In the early stages of traffic-based planning, the goal was to maximise traffic speeds, as discussed in section 6.3.1. As we moved towards more people-centred transport planning, efforts were made to minimise the negative externalities of high-speed traffic, through traffic calming measures such as those illustrated in Figure 10.7. Traffic calming implementations around the world have demonstrated the many benefits of slowing vehicular traffic down, such as improvements in road safety (York et al., 2007), especially for vulnerable road users (Jones et al., 2005), improving pedestrian experience (Huang and Cynecki, 2000) and improvements in physical health (Morrison et al., 2004).

Figure 10.5 The Barcelona Superblock concept
Adapted from http://citiesofthefuture.eu/superblocks-barcelona-answer-to-car-centric-city/

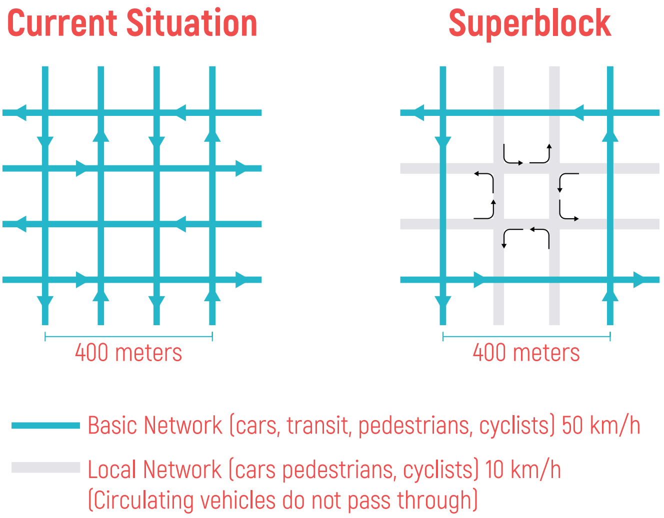


Figure 10.6 High and low-speed road networks and intersection types in the mid-term

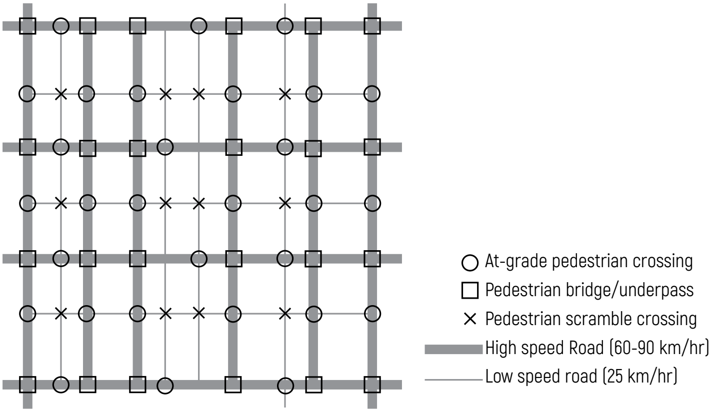
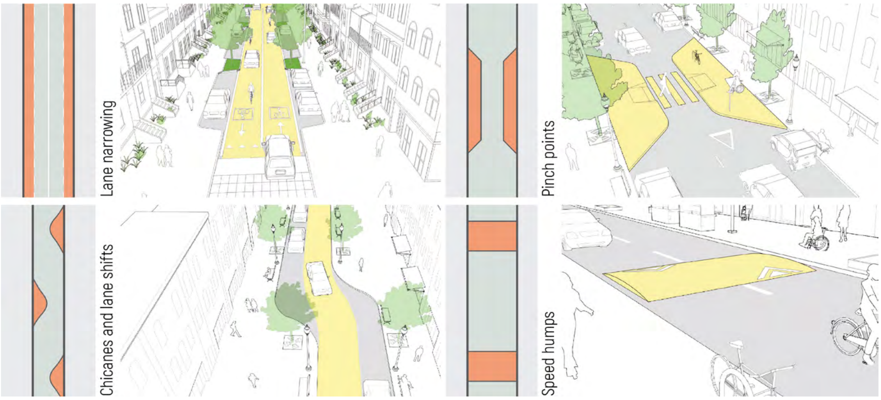


Figure 10.7 Some traffic calming strategies
From NACTO's Global Street Design Guide. Source: globaldesigningcities.org



View on high-speed streets in urban design

Slower traffic speeds are also advocated as a means to achieve more liveable streets in urban design literature (Francis, 1991; Gehl, 2013; Southworth, 2005). Lynch in **Good City Form** (1984) prioritises 'simplicity, flexibility, lack of pollution and openness to all users' over 'speed and technical splendour' for a good transport system. Appleyard's (1981) study of social relations between residents in three streets in San Francisco showed that the residents in quieter streets were able to develop more meaningful relationships with their neighbours. Yet there remains an inherent contradiction between the desire to speed up and the desire to slow traffic down, since time lost in congestion costs businesses money, even if slower streets are considered more desirable in specific contexts (Banister, 2008). This view can be reconsidered in the context of the technological shift in transportation.

How the technological shift changes our notion of travel time

We can question if a 'slower' network necessarily translates to more congestion or travel time, especially with an increase in the use of shared modes, as illustrated in the Network experiment where *superblock* has the most efficient travel time. Vehicle automation would also alter the value of travel time, which points towards a fundamental re-examination of the basis on which 'congestion costs' are calculated. Lyons and Urry (2005) hypothesize that *"as the boundaries between travel time and activity time are increasingly blurred... the 'cost' to the individual of travel time is reduced as travel time is converted into activity time"*. In other words, if part of the travel time can be considered 'productive' time, could this time 'gained' compensate for a reasonable level of congestion?

Will people trade-off increase in travel time with reliability?

Reliability in travel time is also an important determining factor for mode choice (Noland and Polak, 2002). Travellers may sometimes be willing to trade-off longer travel times for more reliability in travel time. Consider the Network experiment where the *grid* had higher average network speed but also had higher levels of congestion and waiting times. Travel time estimations may be less reliable in this case despite faster in-vehicle travel time. The 'slower' *superblock* has slightly higher in-vehicle time than *grid* but delivers the best network performance (ratio of average peak speed to free speed), which may make the travel time estimations more reliable.

Slow network, scramble crossing

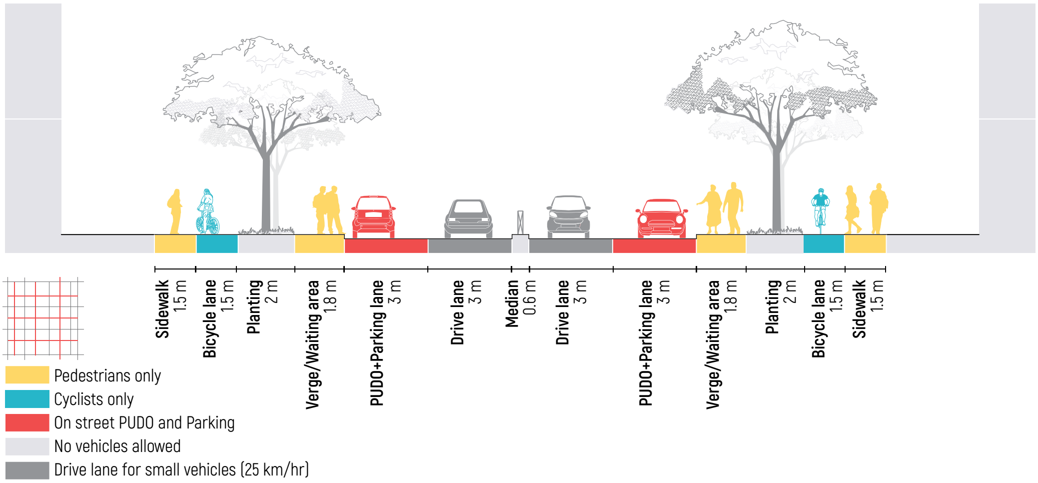
The gains in travel time, overall travel time reliability, and other benefits for urban quality and road safety for vulnerable road users are strong arguments for lowering overall network speeds strategically. We can also expect higher rates of walking with the speed reductions, based on the findings of a walkability survey in Singapore by Erath et al. (2016). Pedestrians can be further facilitated by providing scramble crossings at smaller intersections. Overhead pedestrian bridges and pedestrian underpasses may need to be retained at some locations on the high-speed roads at the periphery of the neighbourhood block, as shown in Figure 10.6. Bridges/ underpasses allow larger DRT vehicles and buses to operate with fewer interruptions reducing the in-vehicle travel time for transit and making it more competitive.

On-street PUDO and Parking

For smaller DRT vehicles to remain competitive with taxis, on-street parking and PUDO should be encouraged. On-street PUDO/ parking improves the access time for DRT vehicles, by reducing the walking distance, waiting time and in-vehicle travel time, as seen in the Parking and PUDO experiments. On some streets, one lane can be blocked entirely for PUDO and parking activity, where only smaller DRT vehicles would be allowed to park for short periods, as shown in red in Figure 10.8. Since the speed on the road has been lowered considerably to 25 km/hr, the lane widths can be narrowed to 3 metres, freeing up enough space to add a bicycle lane on the type 3 roads, as shown in Figure 10.8 in blue.

Figure 10.8 Typical section through road type 3 modified for the mid-term

Note: Road type 3, as defined in the base model, is modified to add one PUDO + Parking lane in both directions. Key plan on the left shows the location of road type 3 on the structural plan.



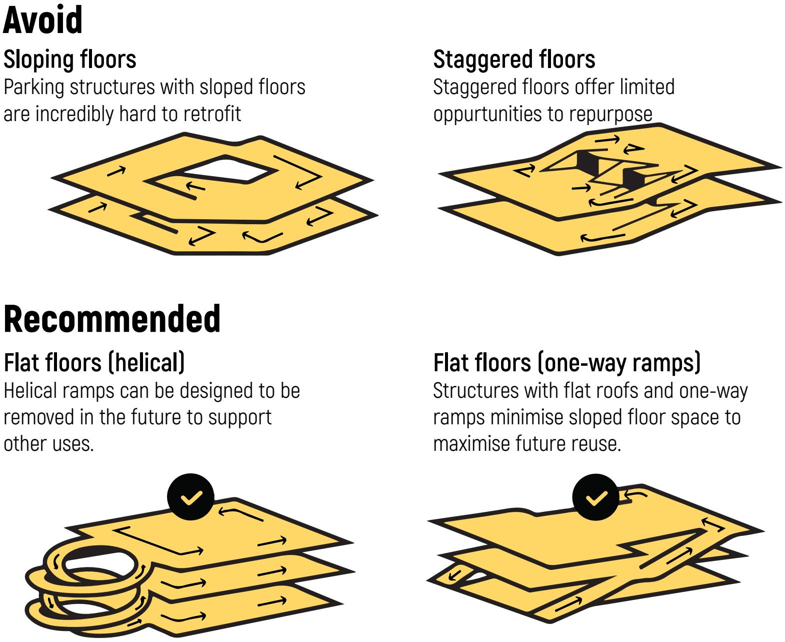
Retrofitting parking

Due to high shared vehicle and taxi use in the mid-term, we can expect a reduction in private car ownership, and consequently the demand for parking infrastructure. Existing parking structures should be further consolidated or adapted to new uses. All new parking structure should be constructed with higher ceiling heights and loading capacity and specific design interventions such as those shown in Figure 10.9, that would enable them to be transformed to other uses in the future. Larger DRT vehicles can continue to park in bus depots.

Need for data sharing

A critical issue for the mid-term future is data sharing between private transport network companies and public transit providers. Transport service for the neighbourhood block/New Town/ city must we viewed as a whole journey and not as separate legs managed by different operators. With more vehicle sharing, optimising the service of the whole system and minimising the friction between the different trip legs is essential, which cannot be achieved without data sharing between different transport providers.

Figure 10.9 Suggestions for parking design to ease retrofitting to other uses in the future.
Source: Adapted from (Gonzales and Ranostaj, 2018)



10.3 Long-term: Imagining a Post-Road City

State of technological development in the long term

In the long term, we can imagine a city where all vehicles – private cars, taxis, DRT, buses and trains – are automated with Level 5 automation. Automated vehicles do not necessarily need to be separated from pedestrians and cyclists since they are expected to function well in shared environments. Greater diversity in vehicle type would be available, such as the examples of shared AV concepts shown in Figure 10.10. This diversity will make private car ownership obsolete. Connected automated vehicles would efficiently drive at high speeds with close spacing since all vehicles have V2V and V2I connectivity. The need for larger DRT vehicles is reduced as smaller vehicles intermittently travel in platoons or branch out when needed. Larger fixed-route automated buses would still need to operate to serve the demand for long-distance and high volume travel. How can we reimagine the New Town Structural model in the context of this long-term future?

The shift can challenge the system of automobility

The technological shift can ultimately enable us to reclaim the city from cars for people. Since the popularisation of the private car, we have been locked into a system of automobility (discussed in section 1.1). As vehicle sharing, automation, electrification, and other technologies comprising the shift become dominant, it can lead to a turning point where this system of automobility can be challenged. According to Urry (2004), the 19th-century 'public mobility' patterns have been *irreversibly lost* to the self-expanding character of the car system. Thus any post car system will still substantially involve the individualized movement that automobility presupposes. The technological shift can enable such a hybrid of 'public mobility' and 'automobility'.

Figure 10.10 Diverse vehicle concepts for shared automated mobility

Self-driving delivery vehicle by NURO
Image source: nuro.ai

Two-seater AV concept smart vision EQ fortwo by Daimler
Image Source: mercedes-benz.com

Four-seater electric automated vehicle concept by Bosch
Image Source: bosch-presse.de

Six-seater autonomous pods being tested in Dubai
Image Source: NEXT Future Transportation

12-seater A shuttles deployed at in Singapore by ComfortDelGro and EasyMile Image Source: Todayonline.com

Driverless bus deployed in NTU campus in Singapore
Image Source: Mediacorp

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[5] This is similar to the DART concept being investigated by TUM CREATE at present. Dynamic Autonomous Road Transit or DART system consists of a fleet of mixed-size modular electric, autonomous road-based vehicles, with secure and high level V2V and V2I connectivity. For more information see (Rau et al., 2019)

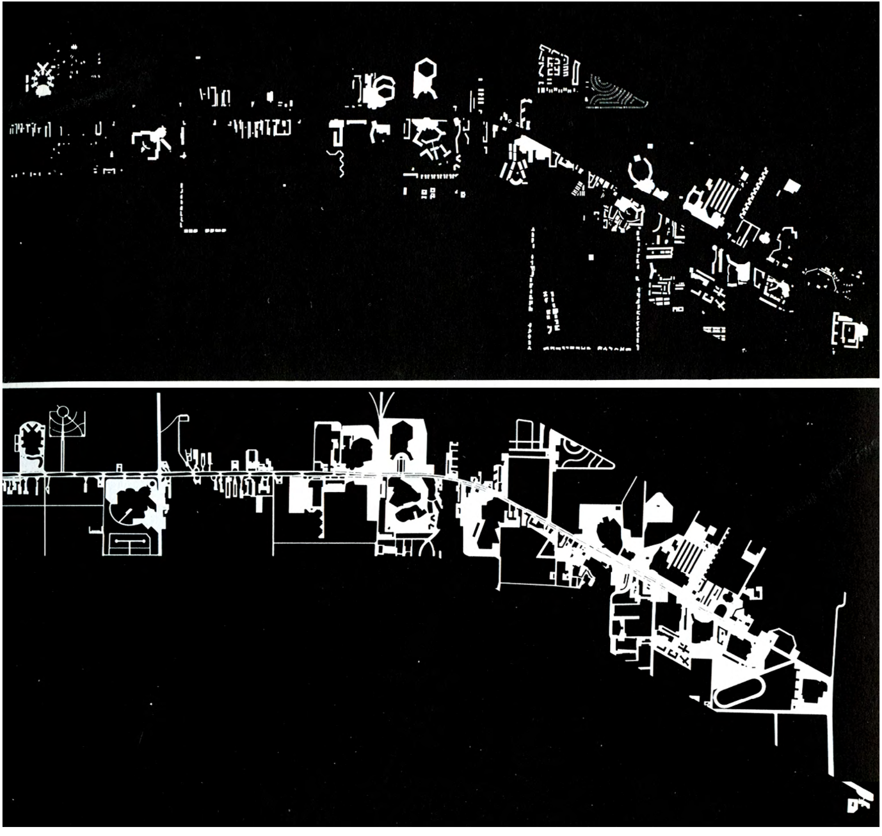
The road before the automobile

The ‘road’ is an integral enabler of the automobility system that must be challenged to support public mobility. Road itself is not a product of automobility per se, and road infrastructure was already quite well developed in Europe and the US, even before automobiles became widespread. However, the quality of road transport was inadequate to effectively compete with railways at the time. Transport speeds on the best road connections in mid-19th century France were well below 12 km/hour (Grübler, 1990). As the age of the automobile arrived, asphalted roads began to provide high speed connections for the car from every node to every node.

The road after the automobile

The pivotal role of roads is evident in the fact that often it is the centrepiece that urban form seems to be organised around (Appleyard et al., 1964). This idea is expressed distinctly in Venturi et al. (1977) seminal work **Learning from Las Vegas**, where the urban form is defined by the orientation of the road, as shown in Figure 10.11. Access to most places, residential buildings, shops and services, is conditioned by the road such that it can be impossible to escape, except by driving to a garage or parking lot (Dupuy, 1995). If the system of automobility is to be challenged, this notion of the road centred around the car must be dismantled.

Figure 10.11 Map of the one mile of the upper strip in Las Vegas.
The building footprint shown above and asphalt footprint shown below. Source: (Venturi et al., 1977)



Roads vs streets

Before the car and asphalt-covered roads, streets were an intrinsic part of the public realm. The words street and road are sometimes used interchangeably but imply different meanings. Etymologically the word ‘street’ is derived from the Latin *sterne*, to pave, which denotes a surface which is part of the urban texture, while ‘ride’, the Anglo-Saxon root of ‘road’, implies passages from one place to another, suggesting movement to a destination (Rykwert, 1986). Thus a street is often seen as a public space (Kostof, 1993), while a road is more a functional artery.

Streets as paths and places

In urban design and planning literature, we see two conceptions of streets. As linear channels of movement discussed earlier in Lynch’s (1960) ‘paths’, Marshall’s (2004) ‘movement space’, and Shane’s (2005) ‘armatures’. The second is as public spaces, discussed in Jane Jacobs’ (1961) ‘sidewalk ballet’, Trancik’s (1986) street as an ‘urban void’, and in writings of other urbanists that describe the street as a place to meet, observe, be observed or get lost (Appleyard et al., 1981; Lynch, 1960; Marshall, 2004). The distinction between the former and latter conceptions has been described as the distinction between the ‘movement’ and ‘place’ functions of the street (Streetscape Guidance, 2019). The ‘road’ is the embodiment of the movement function while the place function is highlighted in pedestrianised streets of historic city centres, or more recently, in designs of car-free neighbourhoods found in Amsterdam, Freiburg and Vienna.

Street as ecology

The ‘movement’ and ‘place’ functions of the street tend to conflict with one another, and it is usual to have one dominate the other. Could the technological shift in transportation allow the two to co-occur? Mehta (2014) offers an alternative view of the street as ‘ecology’, a space of dynamic relationships that results from complex webs of interconnected activities and phenomena. In this definition, the street is both a path and a place at the same time, competing for space for gathering, lingering and movement simultaneously. Such a street is never in a stable state, but always in flux, with an acceptable level of conflict.

Shared streets

In recent times, implementations of shared streets embody this conception of the street as ecology. Shared streets have no formal distinction between spaces dedicated to different modes and movement of through traffic and lingering behaviour of pedestrians co-occur, resulting in a space of conflict through design. Shared streets exhibit some common properties in their design, such as no lane separator marking, a single level of the road surface, no traffic controls and reduced traffic signs (Schönauer, 2017). There is no physical segmentation on the street, but road furniture and design interventions can create guidance and natural segmentation through colour markings, materials or marginal level changes.

Practical application of shared streets

The first formal practical application of Shared streets was in 1970 in the Dutch city of Delft, where a group of residents turned their neighbourhood streets into *woonerven* or ‘living yards’. By increasing the ‘friction’ on the road (as in the friction between different modes), the movement space for the car was turned into shared public space. Urbanists like Donald Appleyard and Jan Gehl, refer extensively to the Dutch *woonerf* initiatives as positive examples of liveable streets. In 2013, shared streets also officially became part of the Austrian Traffic Code through the introduction of the so-called *Begegnungszone* or ‘encounter zone’, such as on the street shown in Figure 10.12.

Benefits and drawbacks of shared streets

These practical applications have shown that shared streets can promote a safer, more vibrant, and multi-modal transport ecosystem while improving travel times for all modes in congested areas (Biddulph, 2012; Wargo and Garrick, 2016). At the same time, shared streets have been criticised for exacerbating challenges with high traffic volumes and accessibility and unresolved questions regarding how children, elderly, blind and sight-impaired people can navigate these spaces.

Shared streets and the technological shift

In the context of the technological shift in transportation, shared streets find new relevance. Automated electric DRT vehicles are smaller, lighter, quieter and cleaner than the traditional automobile, making them less disruptive in a shared space. Better compliance and safety precautions can also be expected from automated vehicles compared to human-driven vehicles. Crucially, the reduction in traffic speeds as a result of the additional friction on the street may not necessarily lead to traffic congestion, if shared vehicles are extensively deployed, as found in the network experiment. The technological shift can be leveraged to challenge the current patterns of automobility, through a ‘Post-Road City’, dominated by shared spaces and shared modes.

The superblock in the post road city

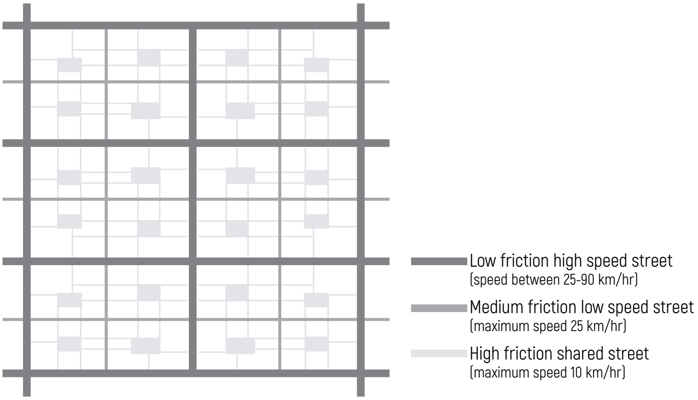
The post-road city is designed using a *superblock* inspired typology of high-speed, low friction peripheral streets combined with slower high friction internal streets, as shown in Figure 10.13. Same as in the base model, the New Town is comprised of six neighbourhoods, and the periphery of each neighbourhood is marked by low friction high-speed streets (in dark grey). Medium friction access streets further bifurcate the neighbourhood. Within each neighbourhood, a network of high friction shared streets is provided (in light grey).

Achieving low friction through grade-separated crossings

‘Low friction’ in the case of the peripheral streets implies that there are very few points of conflict between different modes on the street, which are segregated from each other. High-speed traffic moves along fixed paths, clearly separated from the pedestrian promenade adjacent to it. Underground pedestrian crossings are provided on these streets to minimise stopping instances for vehicles and reduce the points of conflict. Such crossings threaten to create a barrier effect between neighbourhoods and island-like developments. However, the environmental benefits of platooning cannot be entirely realised unless stopping and braking distances are minimised, and the length of the platoon is maximised, as discussed in section 3.1.3. It is crucial to improve pedestrian access to these underpasses through design and provision of escalators and elevators and by reducing crossing distance by minimising street width.

Figure 10.12 Example of a Begegnungszone in Austria
Source: Stadt Flensburg sourced from schwarzbuch.de

Figure 10.13 Diagrammatic depiction of the superblock typology in one New Town



Description of low friction street

All types of vehicles, including automated buses, are allowed to ply on these low friction streets, on one of three paths – access, transition or platoon, as shown in Figure 10.14. A key plan with the location of low friction high-speed streets in the New Town is shown in the bottom left. Vehicles travelling non-stop can do so in the platoon lane in the centre at high speeds of up to 90 km/hr. Vehicles that move slower can travel in transition lane, and those that need to stop or turn can use the access lane. The maximum allowable speed on the access lane is 25 km/hr since it is closest to the bicycle and pedestrian area, as shown in blue and yellow in Figure 10.14. Since all vehicles are automated, lane widths have been reduced uniformly to 3 m. Vehicles can stop at designated PUDO points in the access lane, shown in red in Figure 10.14, or use the access lane to turn into access streets inside the neighbourhood.

Access street

All small vehicles can enter the neighbourhood along access streets, shown in the key plan on the right in Figure 10.15. Access streets have low friction between modes, with clearly marked vehicular, pedestrian and cyclist paths, as shown in Figure 10.15 in dark grey, yellow and blue, respectively. However, they offer higher friction than peripheral roads since vehicles frequently stop at the pedestrian priority scramble intersections and in the PUDO lanes. The outer lanes in both directions of access streets are reserved for on-street PUDO activity and short term parking. This lane acts as a buffer between pedestrians and traffic and frequently transforms into parklets, or wider sidewalks, as shown in the left side of the section in Figure 10.15. Pedestrians can access shared DRT vehicles in only two locations – the on-street PUDO on access streets shown in Figure 10.15 or PUDO points on the low friction peripheral streets.

Shared streets

Smaller vehicles can move further into the neighbourhood on high friction shared streets. ‘High friction’ here implies a high level of conflict and friction between different modes on the street. The shared streets inside the superblock allow pedestrians, cyclists, PMDs and small vehicles, including privately owned vehicles, 1-2 seater taxi pods and service vehicles, to ply at a maximum speed of 10 km/hr. Pedestrians have the highest priority on these streets. Conceptually, these streets can be seen more like a square or a plaza in their design and proportions, similar to the shared street shown in Figure 10.12. Street furniture, paving patterns, lighting and planting can all be used as elements to highlight the movement and place functions of the street.

Based on this new system of shared streets, combined with low friction peripheral spines, we can fundamentally restructure the configuration of built and open spaces in the Post-Road city. One example neighbourhood from the base model, neighbourhood 5, as shown in yellow in Figure 10.16, will be redesigned to demonstrate this concept.

Figure 10.14 Typical section through low friction streets at the periphery of the neighbourhood.

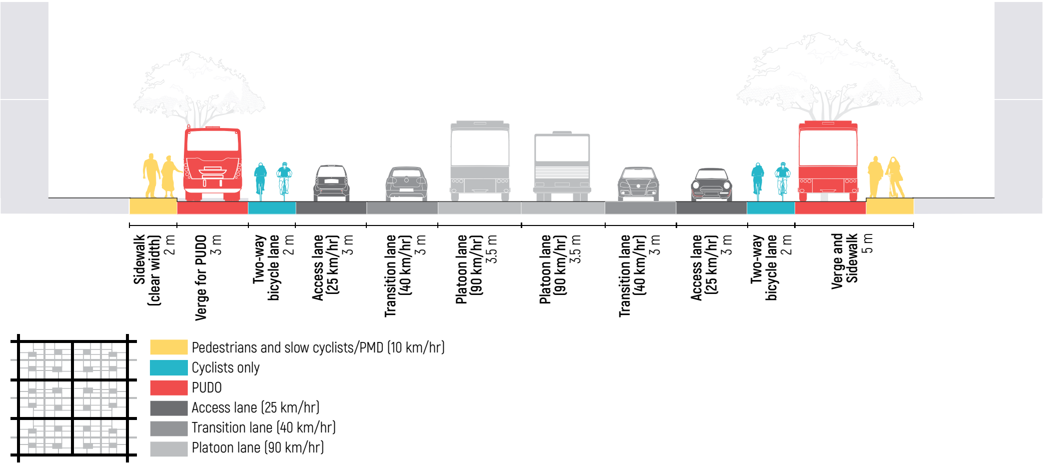


Figure 10.15 Typical section through medium friction access street

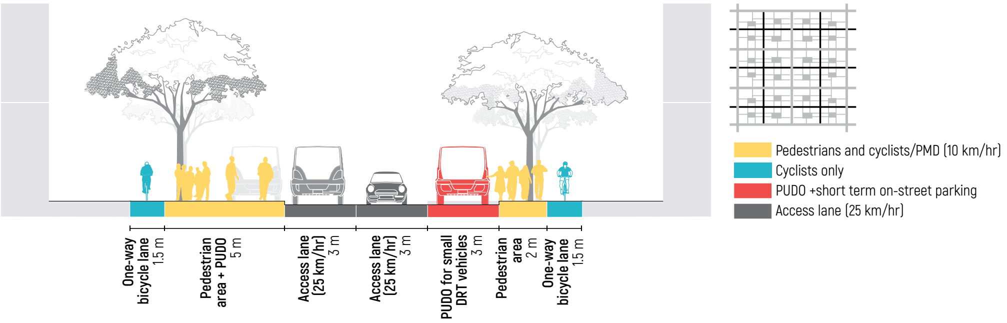
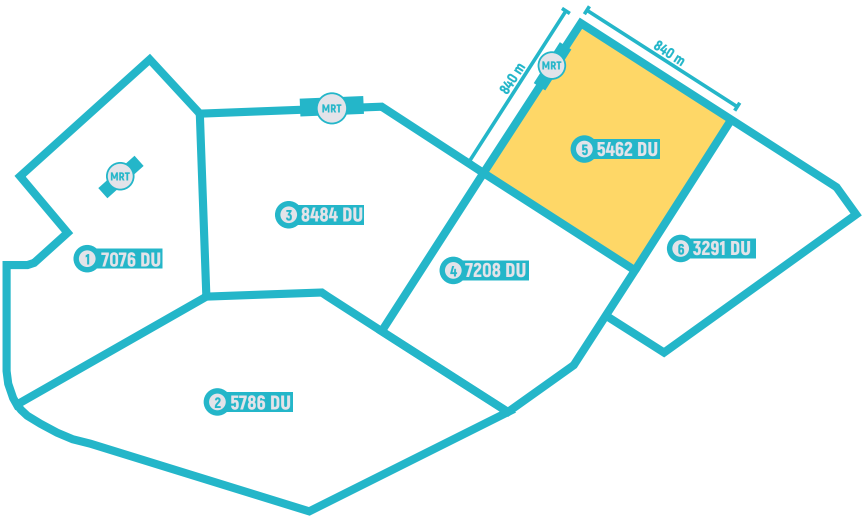


Figure 10.16 Reference plan showing the location of the demonstration neighbourhood



10.3.1 Detailed design of one example neighbourhood

Conceptual design of Neighbourhood

As roads transform into streets that are both paths and places, the current logic of organisation of buildings around roads will become obsolete. A configuration such as that of Las Vegas, shown in Figure 10.11, supports the road as a linear element, with solely a movement function. A new urban configuration is proposed where buildings do not need to 'face a road' anymore, but 'frame' an open space instead. This configuration is demonstrated in the conceptual design of neighbourhood 5 in the Base model. The buildings have all been organized around courtyards which seamlessly connect through the entire neighbourhood, as shown in the bird's eye perspective in Figure 10.17. All courtyards are designed for different purposes. While some courtyards are designated for private use (such as a school), most are publically accessible, and some are even accessible by slow-moving vehicles on designated paths.

Bus path

Different types of users and modes can follow different paths in this configuration. Figure 10.18 shows the variety of paths that can be followed by different modes, through some sample trajectories. Fixed-route transit, or scheduled bus services, are only allowed to ply on the high friction peripheral streets, as shown in light grey. Here they alternate between high-speed platoon lanes and access lanes at designated bus stops. These buses serve long-distance trips, connecting different New Towns, but do not enter neighbourhoods.

Figure 10.17 Bird's eye perspective view of the design of Neighbourhood 5 in the Post-Road City

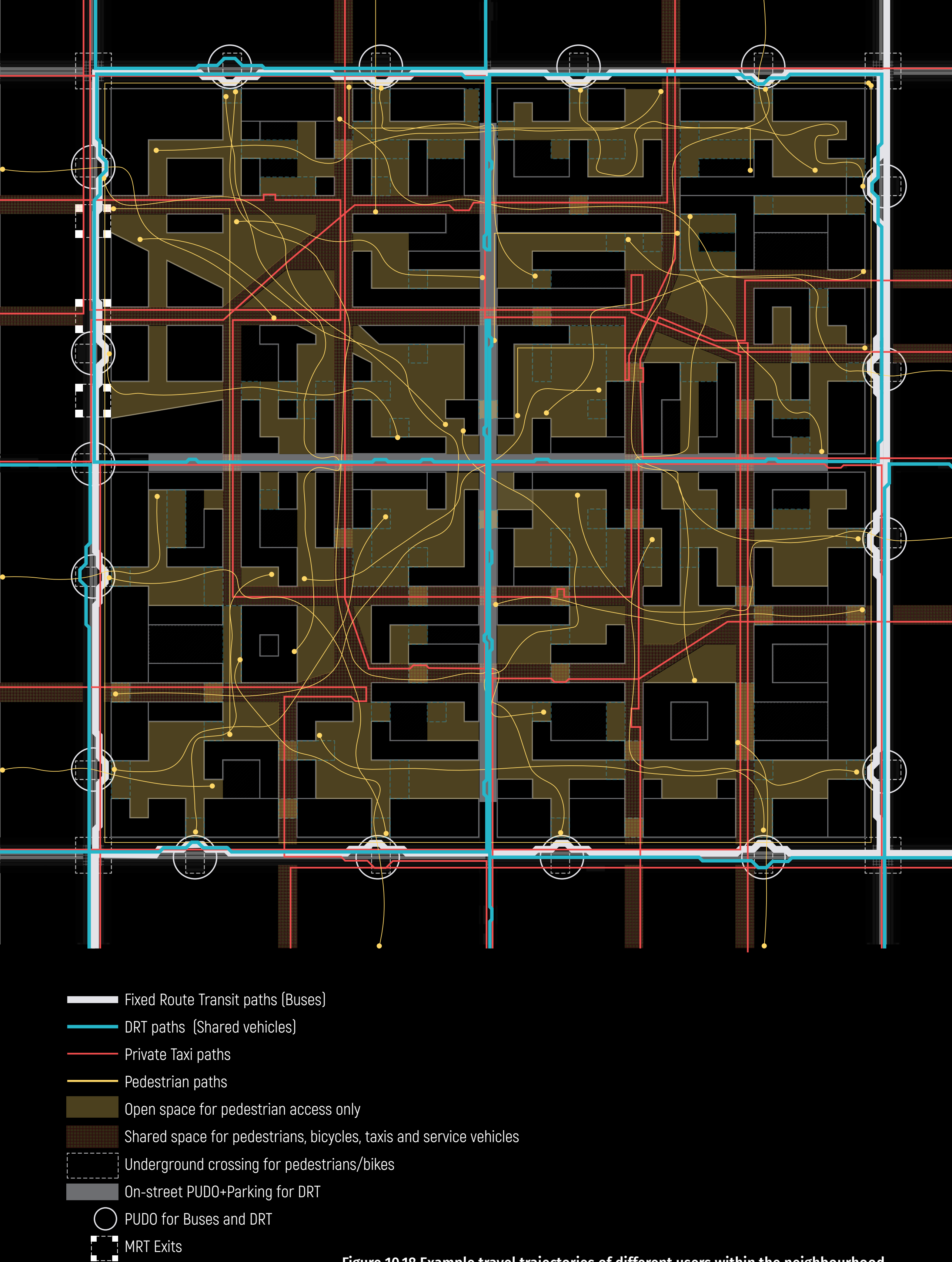


Figure 10.18 Example travel trajectories of different users within the neighbourhood

DRT Path

DRT vehicles (ranging from small six seaters to larger 20 seaters) on the other hand can enter the neighbourhoods through access streets, as shown in the blue path in Figure 10.18. Users can access DRT vehicles at bus stops or anywhere along the access streets. These access streets are narrow and flanked with wide pedestrian and cyclist paths, and intermittent scramble crossings. Note that DRT vehicles do not offer door to door service, which is essential to bundle rides better. However, it is expected that the design of the pedestrian network will allow for shorter and more pleasant walking routes, improving access to DRT.

Taxi path

Small automated taxi bots offer door to door service and travel along shared paths, as shown in red in Figure 10.18. Vehicles such as the two-seater taxi, or automated delivery vehicle, shown in Figure 10.10, as well as small service vehicles are allowed to travel on these shared paths. Taxis could potentially become more attractive here considering the convenience of access at the doorstep. However, given the low speed of travel on shared paths, users may prefer to walk to bus stops or access streets (all designed to be within 300m walkshed) to travel at a lower cost by DRT or bus instead. The design of the pedestrian network plays a crucial role in determining the attractiveness of shared modes compared to taxis.

Pedestrian path

Pedestrians can move through the entire neighbourhood through a series of interconnected courtyards, either following the building envelope or taking a shorter diagonal path, as shown in yellow in Figure 10.18. The elimination of crossing and waiting times at intersection further reduces walking time. The courtyards could be activated with different functions to improve the walking experience, as outlined in the discussion on land use later in section 10.3.2. Outside the neighbourhood, pedestrians can only walk on the sidewalk along the low friction streets, and cross over to other neighbourhoods through underground crossings.

Adding decks and bridges

It is necessary to maintain legibility in such a multidirectional multimodal network, which is why buildings have been strategically lifted to create deck and bridges, that ensure clear lines of visibility. The impact of adding bridges and decks has been analysed in Figure 10.19, by comparing lengths of vistas and open space integration in a site plan with decks on the left and a plan where the buildings are all on the ground plane.

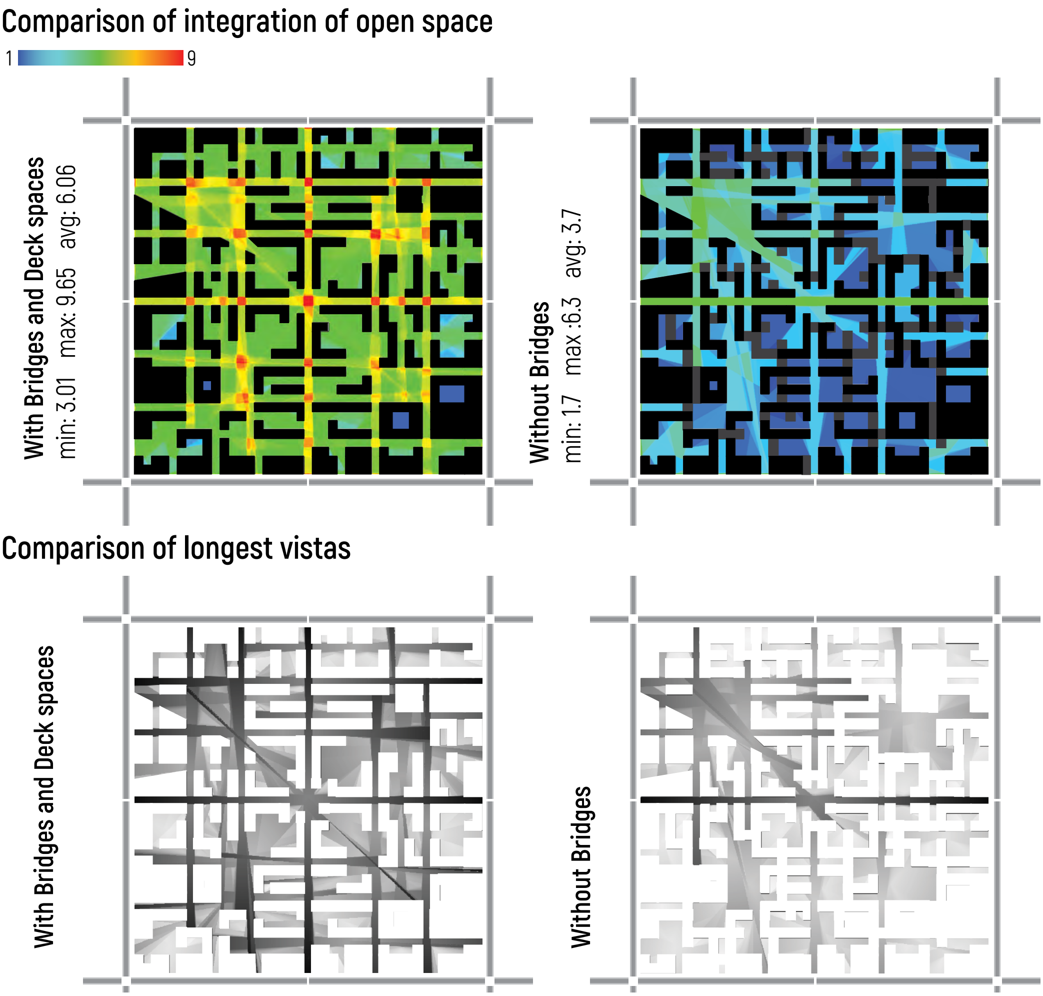
Comparing plans with and without decks

The decks open up the vistas, creating long lines of visibility, as shown in the bottom left of the image, compared to when the decks are entirely built up, as shown on the bottom right. Integration of open spaces has also been analysed, and the average integration is found to be much higher when bridges are provided. ‘Integration’ here refers to a normalised mean of visual depth or the number of steps from one point to any point in the plan, a concept developed by Bill Hillier for ‘space syntax’ analysis in architecture (Hillier, 2015). A high value represents a strongly integrated space, and a low value indicates segregated space.

Territorial adaptation of the technological shift

The new configuration of the Post-road city cannot be limited to merely the building form but needs to be extended to building use. If the car 'unbundled' territorialities of home, work and leisure, fragmenting social practice, creating lengthy commutes and eroding public spaces (Urry, 2004), the technological shift can enable a reversal of this unbundling, allowing a tighter integration between different activity spaces. The flexibility offered by mobility-on-demand systems and freedom offered by vehicle automation could enable new land-use configurations.

Figure 10.19 An analysis of the impact of adding bridges on overall integration and visibility



10.3.2 A discussion on land use in the Post Road City

Problems with fixed land use planning

DRT offers a public transit option that can flexibly adapt to changes in demand, which allows us to move from a fixed land use planning to temporal programming of space use. Currently, we provide a fixed amount of space is provided for specific uses, based on future population predictions. Fixed use spaces are inefficient over time, for example, consider the deserted business districts over weekends, or empty schools during the holiday season. Transport networks connecting these activity spaces themselves remain underutilised during off-peak hours, evident in the parking experiment where the parking structures were found to be empty most of the time.

Flexible land use and where it is at today

Public spaces and buildings need to be designed to be flexible enough to accommodate a range of activity types, sometimes unanticipated, to maximise the use of space. Top-down master planning is already beginning to respond to growing industry calls for greater flexibility in land use. In Singapore, planning of new districts such as Punggol North (Reuters, 2018) point towards this trend. An OECD report on land use governance (OECD, 2017) also recommends more flexible approaches to land use planning, such as the establishment of specific zones in a community which are more open to experimentation and temporary uses.

Bottom-up approaches to flexibility in land use planning

Fixed use top-down planning is also being actively challenged from the bottom up through technological and entrepreneurial disruption in recent years fuelled by the rise of peer-to-peer platforms and automated vehicles. The rise of AirBnb and WeWork signal this shift towards on-demand space use for multiple purposes. A more radical interpretation of flexibility in land use is envisioned by some automotive companies, where an automated vehicle transforms into a clinic on the go or a co-working space. One such example is an autonomous travel suite 'Transpitality', proposed by Aprilli Design studio shown in Figure 10.20, which is a mobile hotel suite (Aprilli Design Studio, 2018). Such vehicles can decouple activities from a fixed space entirely, bring services like a library or clinic to places that do not have to access to them.

How technological shift can support flexibility

While theoretically, such radical ideas of flexibility in land use planning have been around for a long time (Brand, 1995; Friedman, 1997; Habraken, 2008), practically it has been a challenging undertaking. Any implementation runs the risk of uncontrolled development, potentially leading to undesired outcomes such as more sprawl, inefficient transport systems, and incompatible land uses in close proximity (OECD, 2017). Many of these shortcomings can effectively be handled by the integration of mobility-as-a-service systems that can respond better to changes in space use dynamically. As activities become less tightly coupled with places, urban planning methods and procedures would also need to adapt, to support flexibility through architectural interventions and policy.

Space use on the site

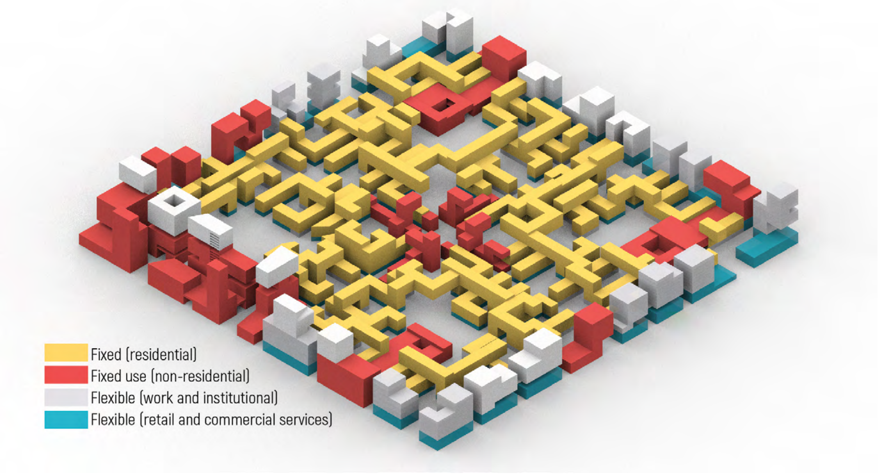
The design of the example neighbourhood discussed before also embraces this notion of flexibility in activity spaces. The entire ground plane is dedicated to non-residential uses, as shown in Figure 10.21. These uses are a mix of fixed (shown in red) and flexible (shown in grey and blue) types. The upper floors are mostly residential in the inner neighbourhood (shown in yellow) and a mix of residential and flexible work and institutional spaces at the periphery.

Fixed use anchors

Consider the ground floor activity plan of the neighbourhood, shown in Figure 10.22. The ground plane is designed as a lattice of built and open spaces, and also that of flexible and fixed use space. The fixed use spaces become anchor locations for the neighbourhood (shown in dark grey). They include three clusters of commercial and office uses near the train station in the north-west, in the centre of the neighbourhood and the south-east. Two sports and recreation clusters are provided in the north and south ends of the site. A cluster for medical facilities are provided in the south-west, and three internal clusters for learning and education are provided in three quadrants of the site. These anchors help in establishing a sense of place and structure for the neighbourhood.

Figure 10.20 Autonomous travel suite 'Transpitality'
Source: (Aprilli Design Studio, 2018)

Figure 10.21 3D of the example neighbourhood coloured by space use



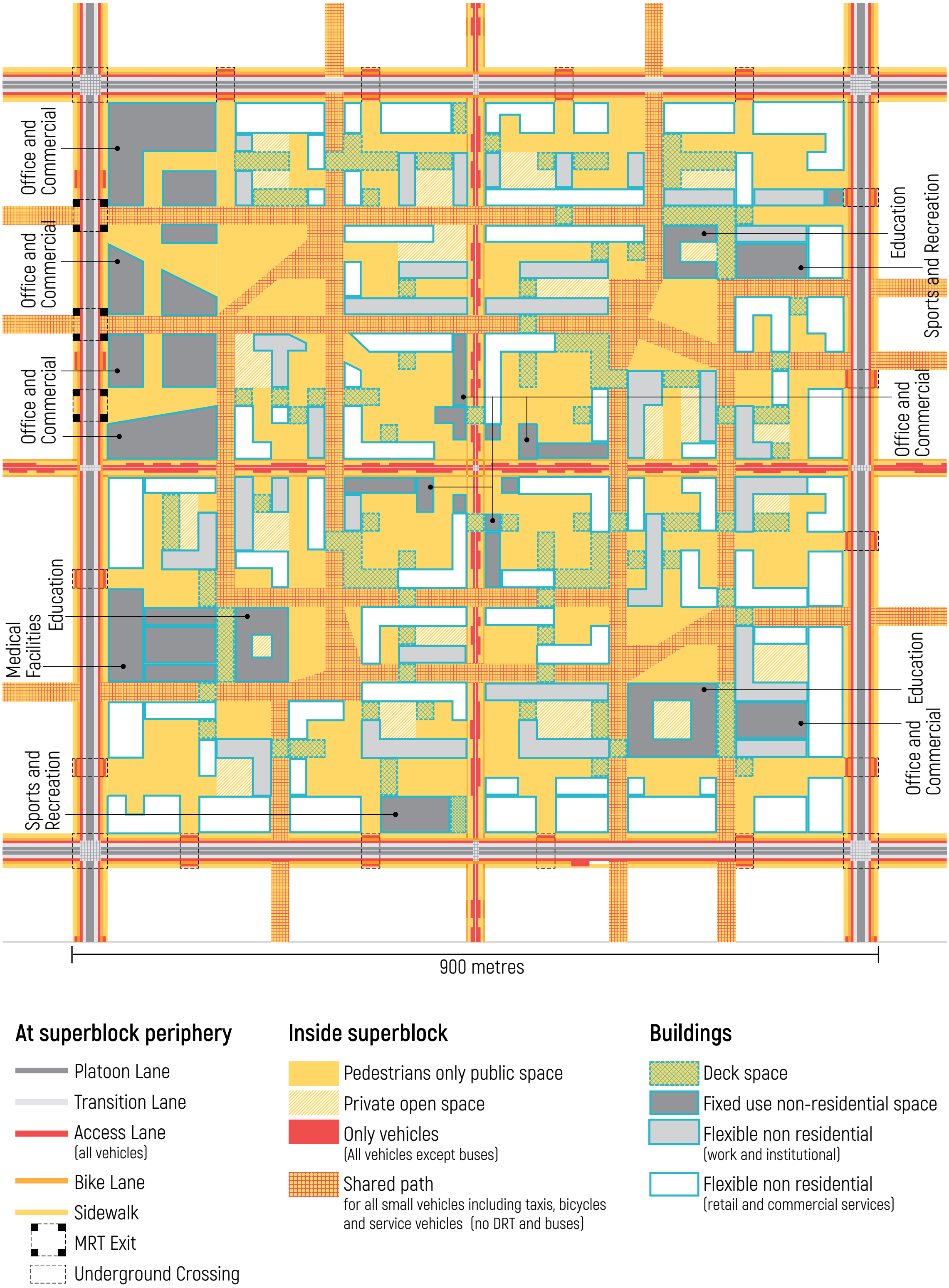


Figure 10.22 Ground floor activity plan of on neighbourhood in the Post-Road New Town

Flexible use spaces

Apart from the fixed use anchor buildings, the rest of the ground floor spaces are designed flexibly to accommodate various types of uses. The flexible non-residential use can be further classified based on compatible uses that can be clustered together, such as a classification based on nuisance factor, architectural requirements, quality of space or type of tenancy. In this case, we classify the non-residential spaces into two types. The first is retail and commercial services, shown in white in Figure 10.22, which includes use such as shops, grocery stores, cafes, restaurants, day-cares, laundry and hairdresser. The second is work and institutional, shown in light grey in Figure 10.22, which includes uses such as offices, maker spaces, art gallery, recreation area and places of worship. The time scale of change in use would depend on local requirements and conditions. A maker space could slowly transform into an art gallery and subsequently an artists' studio over some years. Alternatively, a restaurant could transform into a yoga studio during off-peak hours.

Types of open spaces on the ground floor

This mix of small scale non-residential uses activates the ground floor, and frames open spaces of different sizes, scale and qualities, which form one interconnected whole. Four different types of open spaces can be distinguished in Figure 10.22, privately accessible, shown in a yellow hatch pattern, public open spaces open to pedestrians only shown in yellow, shared spaces for pedestrians and slow vehicles in the red and yellow hatch and 'deck spaces' shown in the blue and yellow hatch, where some private businesses are allowed to spill over, as shown in Figure 10.23.

The HDB void deck

The 'deck space' is a four-story high void space under some residential buildings, forming a new type of covered public open space. This deck space is inspired by the existing 'void decks' in HDB housing. Since the 1970s, HDB has been constructing its public housing on pillars to free up ground-level spaces to create a void deck. The objective of the void deck was to create a shared common space for residents to meet and interact, hold social functions, celebrations and funeral rites. They also inadvertently provide shelter from the elements, promote airflow and allow pedestrians to take short-cuts through the estates.

Proposed deck space as a temporary activity space

Some residential buildings are lifted four stories above the ground plane, bridging the blocks of mixed-use buildings below, as shown in the roof plan of the neighbourhood in Figure 10.24. The space under the bridge is decked and can be used for open space activities, like outdoor seating for cafés. Automated vehicles that provide mobile services are also allowed to park in these deck space, transforming them into a food court, or a mobile library temporarily. The proposed deck space extends these social and environmental benefits of void decks. The higher clear height further improves air circulation and visibility to landmarks.

Land use distribution

On the upper levels of the neighbourhood, the bulk of building space is provided for residential use, mostly concentrated inside the superblock, as shown in the roof plan in Figure 10.24 in white. The periphery of the superblock has a harder edge, with taller buildings and bigger footprints. It interesting to note that due to the space gained from a reduction in road space and parking, a lot more residential units can be accommodated within the neighbourhood. In terms of the absolute quantities, the residential and non-residential area provision is about 50-70% higher than in the base case.

Scope for adding more non-residential area in the neighbourhood

The ratio of residential to non-residential area in the new neighbourhood design is intentionally kept similar to the base case. The percentage of residential area provision in the post-road city is 54% and in the base case 58%. However, a large portion (11%) of the area in the base case was dedicated to parking, which can be transformed into space for other non-residential uses such as industry, work or retail, through flexible use spaces. It will be worthwhile to investigate the land use distribution that is best suited to the post-road city, and further define the elements of the flexible spaces. The dynamics of land-use distribution changes and transport flows are beyond the scope of this research at present.

10.3.3 Pitfalls of the Post-Road City

Criticism regarding fragmentation

One can foresee several issues that could emerge with the post-road city sketched out here. On the one hand, these temporally activated spaces could facilitate increased interaction among residents, and even discourage them from taking longer motorised trips for certain activities that are now locally accessible. However, they could also threaten notions of sense of place and local networks of community, creating seemingly unstructured chaotic urban environments. Each superblock could end up becoming a large-scale 'island-like' development, separated by high-speed traffic and bridges, which could fragment the city in new ways rather than repair the fragmentation resulting from automobility.

Importance of including economic dynamics

Pricing strategy will also play a critical role in determining the success of this model. The same design could encourage greater vehicle sharing and walking, or make private cars and taxis ever more attractive depending on how pricing strategies are implemented. Tax incentives and rent control policies will also play a crucial role in making sure small businesses, essential services and community facilities are not priced out of these flexible use spaces driven by a platform economy.

Risk of creating a digital divide

In addition to the fears of creating physical enclaves, there is also a possibility that the technological shift in transportation will create a digital divide between citizenry. While digital platforms can democratise planning procedures, allowing citizens to shape and change their cities on a daily-basis through information technology, they might also leave those less empowered completely bewildered and excluded. The ultimate goal of our urban design response is to reclaim streets for *all*, and issues of inclusion and equity will need much greater attention in the future, given the risks stated here.

Figure 10.23 View from a shared street towards a deck space
(Produced by author, rendered by Elizelle David)

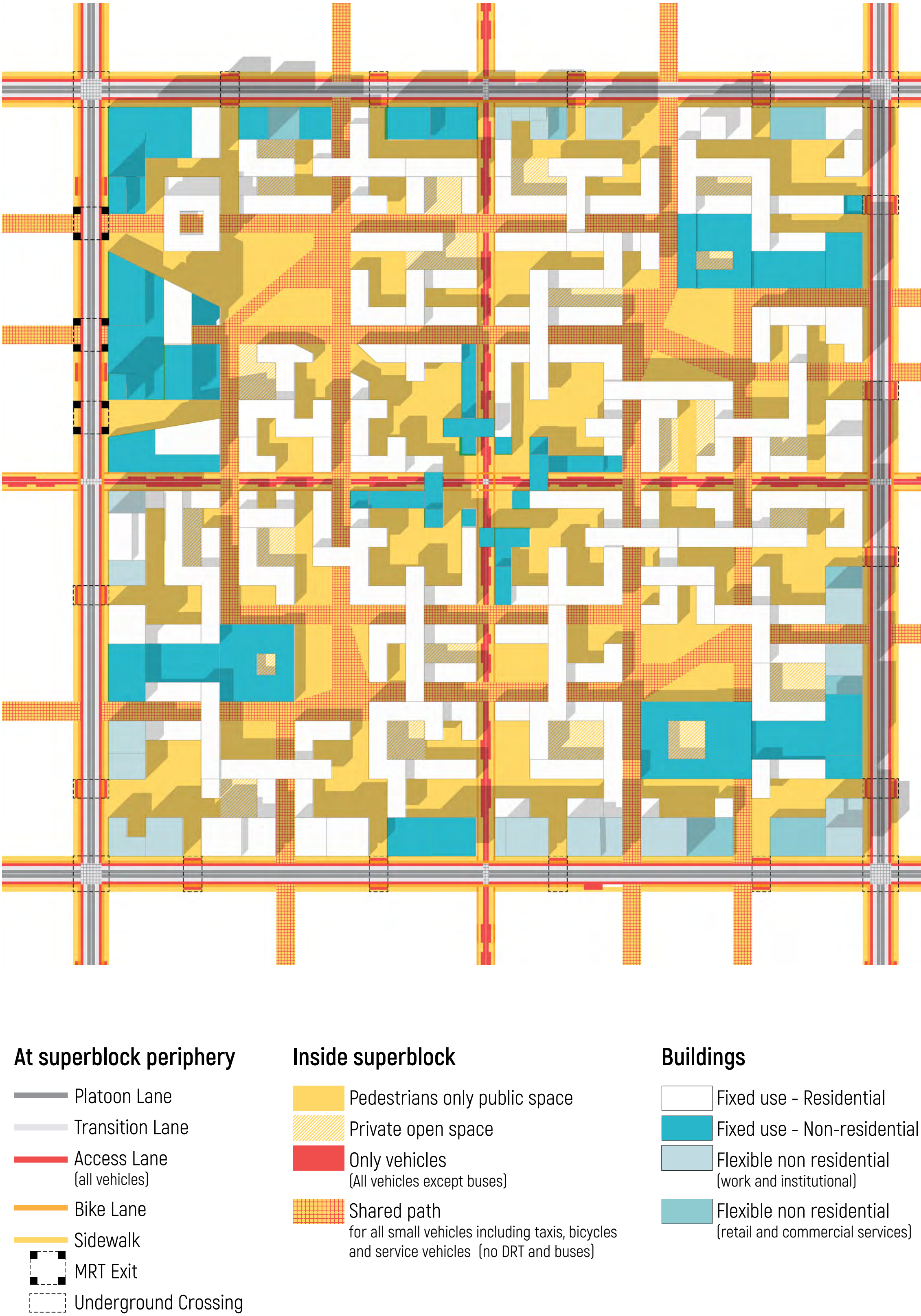


Figure 10.24 Roof plan of the neighbourhood designed for the post-road city

10.4 Principles of urbanism with the technological shift

Through the process of the empirical study, five general principles of urbanism in the context of the technological shift can be derived.

Reconsider the 'Road'

Reimagine road as street

The road as we know it today responds to the car-based mobility system. Large road extension projects facilitated and furthered the automobility system, and urban form also began to be organised around the road as a centrepiece. If the car-based system is to be challenged, the road must be re-imagined as a street, that prioritises people and activities. The technological shift has a unique capability of enabling a street in flux, that can accommodate both its movement and place functions simultaneously.

Reinterpreted representation of roads

The conceptualisation of the road must change not only in its physical form but also representations. Classifying streets by allowable speed limits or the number of lanes may become obsolete in the future. Novel systems of classification would be needed that better represent the role of the street, such as streetscape guidance for London (2019) that uses movement and place function as descriptors of the street, or the high and low friction streets described in this research.

The reinterpretation of the road must also extend to methods of analysis used in transportation planning and urban design. For example, a typical network-based space syntax analysis such as that shown in Figure 8.9, is sufficient to understand measures like connectedness and integration for streets with high movement function. However, for streets with high place function, a spatial analysis, such as that shown in Figure 10.19, may be more suitable. Temporal use of space is an important aspect to be included in the analysis as well.

Understand the temporal use of space

Temporal changes in space use expected more in the future

An understanding of temporal use of space will become critical in the future, in order to avoid infrastructure redundancies and provide for dynamic use of spaces and mobility systems enabled by app-based platforms. Transportation infrastructure should be designed keeping this temporality in mind. For example, street lanes could have different directions, speed limits or uses, on different days of the week, or different time of the day or even hour. How can such a street be designed effectively?

Temporal analysis needed in design

At the same time, design and analysis methods must integrate time and emergence to handle temporal use of space. For example we used agent-based analysis to design specific PUDO infrastructure as demonstrated in section 9.3.4. Time-based usage and design changes must also be visually represented in a more dynamic form than a static geographic or CAD model. How can time be incorporated better in our existing design tools and software?

Embrace walkability

Improving walkability should be the key goal

If the end of private car ownership and vehicle sharing is the preferred future, improving walkability is the key to achieving this goal. A good pedestrian infrastructure supports DRT and DRT, in turn, supports transit. On the other hand, when car and taxi use is encouraged, it is detrimental to all other modes. The key to achieving most of our transport goals such as space efficiency, reduction in emissions, promoting urban vitality, cost-effectiveness and even traffic mobility, is an improvement in pedestrian infrastructure.

Better representation of pedestrian infrastructure needed in transport models

Current transportation models pay very little attention to this aspect and tend to concentrate on traffic flows, abstracting out the pedestrian variables. A finer-grained representation of pedestrian infrastructure quality in transportation models is needed to make a fair comparison between emergent traffic dynamics and its impacts on walkability.

Slow Down

Although automated vehicles can drive faster than human-driven ones, it does not mean they must. A faster network may even generate more VKT and deteriorate walkability of the network. Congestion costs must be reconsidered in light of changes in the value of in-vehicle travel time. Given improvements in transit reliability and in-vehicle experience, slower travel may not remain as unfavourable a proposition as it is today.

Design for Seamlessness

In a future of shared automated mobility, each trip will have more legs on an average than today, which points towards the need for designing more seamlessness between modes. One of the reasons for the better performance of on-street PUDO and Parking in the experiments could have been the seamlessness of access. According to Urry (2004), the seamlessness of the car journey makes other modes seem fragmented. The gaps between various mechanised means of public transport are sources of inconvenience, danger and uncertainty.

An easy interchange between train-bus-DRT-pedestrian-cyclist-PMD is essential to ensure the success of shared systems. Seamlessness could be enabled through the location of mobility hubs (integrated, or tightly connected through legible networks), design of PUDO (high visibility, multiple access points) as well as the design of the vehicle (wider doors, more entry points, vehicle floor height). However, the idea of modal separation by grade, as shown in the low friction streets of the Post-Road city, goes counter to this notion of seamlessness.

11 Reflections

We have used a multi-disciplinary approach in this research to prepare an urban design response to the technological shift. We will now reflect upon this research process through three lenses. First, we reflect on the role of urban design in the context of the technological shift in transportation. Second, we deliberate on the extent to which the methodological framework used here was successful in handling the challenges posed by the technological shift. Finally, we list the issues and problems that remain unhandled and must be addressed in future work.

11.1 On the role of urban design

Challenging automobility through the technological shift

The widespread proliferation of the private car locked us into a system of automobility for decades, and it is this system that we hope to dismantle using the technological shift in transportation to establish new more sustainable patterns of mobility. The car is the primary instrument of the system of automobility, which is enmeshed in a complex of web social, economic, political and environmental conditions. It is clear that merely replacing one technology, in this case, the car, with another, does not dismantle this complex system. Broader societal changes need to be instituted within a favourable environmental and economic climate for such a transformation. Urban design plays a small but significant role in this larger process.

Kevin Lynch presents a very humbling view on this when he says that

> *"regardless of any influence it may or may not have, physical form is not the key variable whose manipulation will induce change ... our physical setting is a direct outcome of the kind of society we live in".*

Can urban design play a role?

However, he concedes that physical change can *'support and even induce social change'.* It is this capacity of urban design that we explored in this thesis. At the end of this research, we can definitively say that urban design can steer the impacts of the technological shift towards a desirable state if it takes a more purposive stance in the current debates regarding the technological shift. According to some scholars, that has not been the case so far.

Urban design searching for a footing

Urban design as a discipline is yet to find a voice in the debate surrounding AVs and other transport technologies. The pace of planning and development in cities is unable to match the rapid advancements in new technology (Noyman et al., 2017). Papa and Lauwers (2015) warn that the transport sector is becoming increasingly techno-centric and consumer-centric, where the users are seen as passive consumers of increasingly sophisticated technological solutions imposed upon them. In 1956, Owen (1966) posed a broad question with regards to the burgeoning car consumption and highway construction. *"Should the city adapt to the automobile, or should transport technology instead be adapted to the existing patterns of urbanisation?"* Through this research, it has become clear that neither must be pursued.

Role of urban design

The citizens, users and city makers, need to find an active voice in the process to *collectively* define a desirable urban future, which must then be pursued by adapting the technology *and* urban form. One can counter that there could be no *one* desirable urban future given the plurality of interests in any community. The role of the planner and urban designer is, as Lynch (1984) declares, to *'clarify the course of that conflict by presenting information on the present form and function of the city, predicting future changes and explaining the impact of various possible actions'.* This thesis set out to do the same, through workshops, stakeholder consultations, design experiments and the design scenarios. Were these methods successful in achieving the objective outlined here?

11.2 On the effectiveness of the methodological framework

Three novel aspects of the methodology

There were three novel aspects to the proposed methodological framework. The first was the active engagement with stakeholders to produce knowledge through an action research process. The second was the use of exploratory modelling, that is, using partial information to pursue partial answers. And finally, the integration of the urban design and multi-agent simulation models in a seamless workflow.

Benefits of engagement

The collaborative process grounded the research in practice and helped tremendously in managing the scope of research. The critical decision-makers in government agencies were also able to 'rehearse the future' (Lyons, 2015), by actively engaging in the research process. An exhaustive list of uncertainties, drivers and assumptions were gradually revealed to the actors through this process, rather than having results produced by some black-box model thrust upon them in the end.

Problem of effective communication

An essential part of such collaborative processes is the communication of design proposals and research findings. The knowledge produced needs to be translated between disciplines, which sometimes speak very different languages (which especially true in the case of engineering focussed vs design-driven disciplines). At the same time translation is also required between researchers who are subject area experts and policymakers, who tend to be generalists. There are plenty of software and tools available today, that facilitated such knowledge transfer and sharing through data visualisation and interpretation.

Design thinking methods for collaboration

Design thinking methods were, in particular, found to be useful in facilitating collaboration. Design allows our imagination to run more freely, gives material expression to theoretical insights, grounds these imaginings in everyday situations, and provides a platform for further collaborative speculation (Dunne and Raby, 2013). For example, design workshops proved to be very useful in establishing a feedback cycle between theory and practice. The workshops focussed on 'learning by doing', where the participants were asked to design a neighbourhood integrating AVs, based on research outputs. Since most of the participants did not have a design background, they were provided assistance to help them translate their ideas. The design workshops were much more effective in communicating research findings than a report or presentation. Working with visual scenarios that represented research findings in a physical space, through the short, mid and long term futures, were also useful in eliciting a response and sparking debate.

Issues with building consensus

Building consensus among all stakeholder to develop the design experiments and define performance measurement criteria was a difficult challenge to address. The process of arriving at a single set of assumptions and performance measures, that met the requirements of all stakeholders, within the technical and site constraints, was long-drawn and contentious. Even if consensus on a set of assumptions is reached, it is always subject to change, following policy changes or unforeseen new developments within the short three-year span of the project. Consequently, instead of pursuing accurate results, the focus shifted towards building more agility into the tools and procedures used for both design and simulation.

Challenge of reconciling two disciplinary workflows

Urban design and simulation workflows tend to be very different where the former can be highly iterative and intuitive, as opposed to a traditional empirical predictive process, where iterations are fewer. Reconciling the two workflows presented many challenges, for example, for every design alteration, however minor, a whole new demand description and network needed to be set up in a simulations model which can be very time-consuming. The larger the area of simulation (or the number of agents), and higher the level of complexity (for example, DRT instead of fixed bus network), the longer is the run time of the simulation, which cannot match the quick iterative pace of design workflows. Finally, design elements of interest, such as parking design, may not be explicitly manipulable inputs for the simulation. Given these constraints of model set up time, simulation run time, and low spatial granularity, the integration of design and simulation was severely restricted.

Effectiveness of exploratory models

Exploratory modelling was a deliberate effort to build agility into the research process, which allows us to test several options fairly quickly, by only building partial models. The design was stripped down to its essential elements that have a direct relationship with transport flows, as evidenced through literature review and workshops. Therefore, some design layers, such as topography and vegetation, were abandoned later in the parametric model. Development of an agile version of MATSim, 'Sketch MATSim', allowed quick evaluation of design scenarios at the required spatial granularity. However, it must be acknowledged that if the model is too simplistic, the significance of the results might be compromised. Low level of detail may also mean that when the differences between results are too small, it is difficult to attribute them to any particular system dynamics, as was the case in the Parking experiment.

Problem of personal bias in exploratory models

Researchers collectively decide, in consultation with stakeholders, what details need to be represented in an exploratory model, which meant that such models could be ridden with personal biases. For example, land use distribution was identified as a critical factor in influencing transport flows. However, it was not included in the design experiments since land use provision is relatively stable in Singapore, with most of the residential land being publically held by a central authority. In order to check this bias, only 'structural results' were pursued through design experiments. Multiple answers were encouraged for the same problem, without pursuing a single correct 'solution'. As new stakeholders participate in the process, or new concerns emerge, subsequent experiments may refute the conclusions of these experiments.

Exploratory model as a mediating object

It is crucial to view exploratory models as a persuasive storytelling tool, or a pedagogical tool or, as in this research, a mediating object to test, modify and change according to different needs and preferences of the stakeholders involved. The insights from the application of complex analytical models cannot be used to predict the future, but are only useful as long as they are seen as tools for the elaboration of contested visions, where the debate itself can be an informal way of assessing technology and enabling social learning (Mladenović, 2019). After all, future itself is not a '*single grand vision or an inevitable consequence of trends, but rather an object of manipulation, discussion, debate and eventually, consensus*' (Wachs, 2001).

Advantages of ABM to understand temporal use and emergence

The third innovative aspect was the use of multi-agent modelling in conjunction with urban design to build insights which proved to be highly beneficial. The simulation results offered a temporal perspective that is almost completely lacking in traditional design methods. Some findings from the design experiments, such as the temporal use of PUDOs and parking, allowed a better understanding of how to design transport infrastructure for more efficient use over time. Simulations also allowed us to understand emergent effects in a complex dynamic system, such as the trickle-down effect of walkability improvements for all modes. Some of these conclusions may have been overlooked in the absence of agent-based analysis, evident in the stark difference between speculations (Tables 9.1, 9.2, 9.3, 9.4) and simulation results (Tables 9.10, 9.16, 9.19, 9.21) of the design experiments.

Advantages of integrating design in ABM

By tightly knitting together urban design and simulation processes, not only were the design proposals better informed, but the description of the simulation model also improved. Agent-based models have often been criticised for their difficulty in practical applications, either due to their resource intensiveness, data hungriness or difficulty of comprehension and manipulation by non-experts (Klügl and Bazzan, 2012; Perez et al., 2017; Rasouli and Timmermans, 2014). According to Bonabeau (2002), an agent-based simulation model must be built '*at the right level of description, with just the right amount of detail to serve its purpose; this remains an art more than a science*'. The design inputs helped to develop a model description that targeted specific practical applications, pruning away superfluous details. By running quick sketch simulations through a visual interface in Sketch MATSim, a non-technical expert could reconcile both urban design and simulation models in one space.

Sketch MATSim has some way to go

Sketch MATSim remains a product under development, and a considerable amount of technical expertise is still required to build the simulation model. Implementing new design strategies and policy measures (for example, implementation of road pricing), requires technical expertise. Demand estimation, in particular, remains challenging since MATSim does not model travel demand endogenously, but needs exogenous estimation of travel demand choices. Further developments in Sketch MATSim are required to ease the demand generation process with diverse land uses, for a non-technical user. As the land use descriptions get more complex as in the Post-Road City, it will be even more difficult to incorporate these dynamics without severely compromising computation time.

Validation and calibration

Other issues regarding model validation and calibration persist for agent-based modelling in general (Iacono et al., 2008; Klügl and Bazzan, 2012), and Sketch MATSim in particular. Validation helps us to determine whether an unexpected result of a simulation is due to the system dynamics or a programming mistake. Here we support the view taken by Bankes (1993) regarding validation and sensitivity analysis, that these concepts are only relevant for consolidative modelling. In the case of exploratory modelling Bankes (1993) says, *"issues of quality for exploratory modelling must be cantered on ensuring the validity of the analytic strategy. Model-specific quality control issues are limited to verification that the model is plausible and that the software implements the model intended".*

11.3 On assumptions and limitations

Constraints of site, stakeholders and software

The empirical section of this research was strongly tied to a physical context, that of New Towns in Singapore. Thus the design response is localised to the context, and a different site with different physical conditions and social context may produce entirely different results. Similarly, since the study was designed in consultation with a particular stakeholder group, an entirely different stakeholder group may produce different results. Finally, the simulation platform used in this research, MATSim, is one of many transportation simulation packages available today. The technical constraints and simulation logics vary between them, and a different simulation framework may yield a different research design and result. Thus the research results must be viewed in the context of the assumptions and limitations posed by the constraints of the site, stakeholders and software.

Description of pedestrian features missing in simulation model

A critical limitation of the MATSim in the context of this research was the insufficient representation of walkability related features. Variations in the beeline distance factor were taken as a proxy for the differences in approximate walking distance based on network connectivity or intersection design. Due to their mathematical nature, simulation models tend to focus on measurable variables like traffic flow, ignoring more subjective notions such as comfort, status and convenience (Kane, 1972), which are even more relevant for active mobility flows. If our goal is to dismantle the system of automobility and reclaim road space from vehicles for people, a finer-grained description of the pedestrian network is needed.

Need to add additional pedestrian layer in MATSim

While presently the pedestrian and vehicular traffic operate on the same network layer in Sketch MATSim, eventually a pedestrian network layer, entirely separate from the traffic network layer, must be included in the simulation model. The links in this layer can be weighted by various attributes such as elevation difference, presence of interesting urban design features, or integration and legibility of the network based on space syntax analysis. Such a weighted pedestrian layer can better incorporate urban design inputs in a mathematically manageable format required for a MATSim model.

More nuanced indicators needed

The indicators used to measure the performance of the transport systems can also be more nuanced. For example, VKT is used here as a proxy for the level of emissions and environmental sustainability. However, other environmental factors can easily be included in an agent-based analysis, such as exposure to air and noise pollution, and availability of greenery and open spaces. The current set of indicators provided by Sketch MATSim could be extended to include such indicators.

Pricing needs more investigation

Several assumptions were made in order to simplify the simulations and reduce runtimes, as summarised in Table 8.1. The subjects of many of these assumptions merit a targeted study in their own right, given their important role in influencing transport flows. For example, the pricing strategy, specifically DRT pricing and road pricing, has a strong influence on the performance of the transportation system. How can we design a pricing strategy that controls overall VKT generated while maintaining equity of access and affordability?

Under-representation of some issues in the models

Many aspects of urban quality and transport flows were not visualised in the design model or considered in the simulation model. For example, the question of traffic segregation was investigated from the point of view of efficiency of space use, traffic flow, active mobility and transit access, but not traffic safety, which is a primary driving factor in this decision. Cost of building new infrastructure is also not taken into account, which in some cases can be quite prohibitive. Similarly, reliability of transit service and apps used for booking is an important influencing factor, as discussed in Section 10.2. Level of acceptance of technology by the user plays a decisive role in determining mode choice, especially in an ageing society such as Singapore. Due to under-representation in the models, these factors may have been ignored in the overall assessment of the design proposal.

Missing transport flows in the simulation

Some types of urban transport flows are excluded from the simulation model, such as freight and service traffic, which accounts for a large proportion of transport flows in the city. These flows will be critically impacted by the rise of e-commerce and on-the-go services. Vehicle maintenance and charging behaviour would also create a significant number of new trips. When charging behaviour is taken into account, the detour factor and ride bundling levels may also change, as shown by some quantitative studies (Bauer et al., 2018). When these additional transport flows are included, the results of the simulation may vary.

Land use and decoupling of space from use

A key variable not investigated in this research is land use mix and diversity. Additional experiments to test these variables are recommended for future research. Especially pertinent is the decoupling of space use from fixed space, in the context of the Post-Road City. Current activity-based models typically differentiate between activity and travel episodes, but the technological shift will blur the boundaries between the two (Rasouli and Timmermans, 2014). Activity-based models would need to be updated in the future to accommodate this decoupling.

Challenges of implementation

The challenges of implementing some of the more radical ideas proposed in the Post-Road have not been addressed so far. The implementation of the Barcelona Superblocks offers relevant lessons in this regard. According to Zografos et al. (2020), it is not about the character of the initiative itself, but the implementation of the initiative that need attention, since is often confronted with unavoidable socio-political barriers. Future research must embrace action research to tackle this, and chart out a path towards a collectively defined preferred future, rather than presenting a single grand vision.

Failings of the technology

Finally, one must end with an acknowledgement of failings of the technology itself. A stable path of technological development is assumed here, which is unrealistic based on the trajectory of any technological development through history. Technology can fail, or new technologies can emerge in the long term, setting us upon a completely different path. The ongoing global crisis triggered by the COVID-19 pandemic is an excellent example of societal disruption that can change of course of previously predicted developments.

The pandemic and the technological shift

At the time the early sections of this dissertation were being written, the idea of flexible multi-use space was considered important but not relevant in the near term. As urban areas around the world began to successively lock down starting February 2020, a new normal emerged. Tactical architecture interventions transformed public spaces overnight to enforce social distancing. An expo centre transformed into an isolation facility (Basu, 2020), our homes transformed into offices, and our offices moved to a virtual space. Some commentators even proclaim this as the end of the office as we know it (Molla, 2020). Mobility as a service and vehicle automation have found new relevance as the world grapples to respond to the COVID-19 pandemic, striving to reduce spread of infection through social distancing measures on the one hand, and attempting to resume economic operations post a protracted lockdown to revive the economy on the other. Modularity and decentralisation are key tactics to approach these challenges, both in design of transportation infrastructure as well as land use planning. The technological shift can potentially support both this tactics effectively.

Honing our tools to become more agile

The recent pandemic strongly has demonstrated the great uncertainty that surrounding urban planning decisions in an increasing complex and interconnected urban ecosystem. But, even as technological developments within their physical, social, economic and environmental contexts become increasingly uncertain, our design goals and intent remain relatively stable over time. Given this, the development of agile planning methods and tools, that include time, emergence and human behaviour in analysis and representation, becomes even more valuable than the outcomes presented in the preceding chapters. In the future, we will draw many blueprints for a future city, and redraw them when faced with new challenges, but today we must take the opportunity to hone our drawing tools.

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Appendices

13.1 Appendix 1: The L2NIC-AV Project

13.2 Appendix 2: Design Workshops

Appendix 1: The L2NIC-AV Project

The L2NIC project

One of the critical goals for Singapore's long term development is to support sustainable growth, and good quality of life as population growth continues to put pressure on the already limited land resource. The Land and Liveability National Innovation Challenge (L2NIC) is a long-term, multi-agency effort that recognises land as a precious resource to Singapore, and seeks to leverage on R&D to provide sustained capacity and options for future generations. In 2016 the L2NIC grant was awarded to a proposal exploring urban planning and policy for automated vehicles in Singapore.

The L2NIC-AV consortium

This thesis is a part of this three-year research project - Studying Autonomous Vehicles Policies with Urban Planning of Toa Payoh in Singapore (Award No. L2NICTDF1-2016-3, heretofore referred as 'L2NIC-AV project') – awarded to a consortium of three academic institutes – MIT SMART (Singapore-MIT Alliance for Research and Technology), Future Cities Laboratory, SEC (Singapore ETH Centre) and NUS (National University Singapore). This project has four main objectives:

1. Simulation study on baseline urban and transportation plan for 2030
2. Optimise urban plans based on simulation study and refine the simulation
3. Develop design principles for the integration of AV infrastructure in existing towns in Singapore
4. Simulate entire island with AVs

Workflow

The project brought together strong expertise in automated vehicles from urban planning, spatial analysis and transportation simulation, and applied them in a study tailored to Singapore's unique high-density tropical urban environment. The study focussed on the deployment of AVs in both greenfield and infill sites to study suitable urban design and AV operation schemes for implementation. AV deployments in both mixed traffic and only automated traffic conditions are simulated using two agent-based simulation platforms – MATSim and SimMobility. The results from the simulations inform design principles for AV integration in New Towns in Singapore, as illustrated in Figure A 1, and generate an optimised urban plan for the site. AVs are also simulated island-wide to see how their deployment would impact transport supply.

Collaboration with government agencies

The L2NIC aims to fund R&D projects that have a high potential for practical implementation in the areas of land creation, land savings and enhancing liveability and environmental quality. To ensure the effective translation of research into practical solutions that can be test-bedded and deployed, close collaboration across Singapore's planning and development agencies and industry is encouraged. There are four Singapore agencies officially collaborating on this project – Ministry of Transport (MoT), Urban Redevelopment Authority (URA), Land Transport Authority (LTA) and Housing Development Board (HDB). The dual focus on real-world problems and developing solutions through collaboration made it ideally suited to 'action research'.

Two types of interaction

This PhD was informed by two types of interactions in this project. The first involved close interactions with experts in agent-based simulations for transportation, which influenced the research methodology. These interactions were facilitated through the transdisciplinary nature of the L2NIC project team and the shared working space. The second involved frequent interactions, both formal and informal, with government agencies, which influenced the problem and scope definition. These interactions took the form of reporting meetings, working-level meetings, team update meetings, training sessions, design workshops and technical workshops. A timeline of formal interactions is shown in Table A 1.

Table A 1 Timeline of formal interactions during the 3-year research process

Date	Title	Attendees
26 Jan 2017	Kickoff Meeting	SEC, MIT, NUS, MoT, URA, HDB, LTA
3 Mar 2017	Technical Workshop 1	SEC, MIT
10 Mar 2017	Design Workshop 1	SEC, MIT, NUS, MoT, URA, HDB, LTA
4 May 2017	**Y1Q1**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
9 May 2017	Technical Workshop 2	SEC, MIT
13 June 2017	Technical Workshop 3	SEC, MIT
18 July 2017	Design Workshop 2	SEC, MIT, NUS, MoT, URA, HDB, LTA + experts[1]
27 July 2017	**Y1Q2**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
3 Aug 2017	Design Review Meeting	SEC[2], URA
25 Aug 2017	Working level meeting 1	SEC, MIT, NUS, MoT, URA, HDB, LTA
16 Oct 2017	Technical Workshop 4	SEC, MIT, NUS
10 Nov 2017	**Y1Q3**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
31 Jan 2018	Working Level Meeting 2	SEC, MIT, NUS, MoT, URA, HDB, LTA
5 Feb 2018	Technical Workshop 5	SEC, MIT
23 Feb 2018	Design Review Meeting	SEC[2], URA
27 Feb 2018	**Y1Q4**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
2 Mar 2018	Design Review Meeting	SEC[2], URA
23 May 2018	Working Level Meeting 3	SEC, MIT, NUS, MoT, URA, HDB, LTA
4 June 2018	**Y2Q1**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
18 July 2018	Technical Meeting 6	SEC, MIT
24 July 2018	Design Review Meeting	SEC[2], URA
29 Aug 2018	**Y2Q2**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
6 Sep 2018	Working Level Meeting 4	SEC, MIT, NUS, MoT, URA, HDB, LTA
18 Oct 2018	Design Review Meeting	SEC, URA, HDB
5 Nov 2018	Design Review Meeting	SEC[2], URA
26 Nov 2018	Design Review Meeting	SEC[2], URA

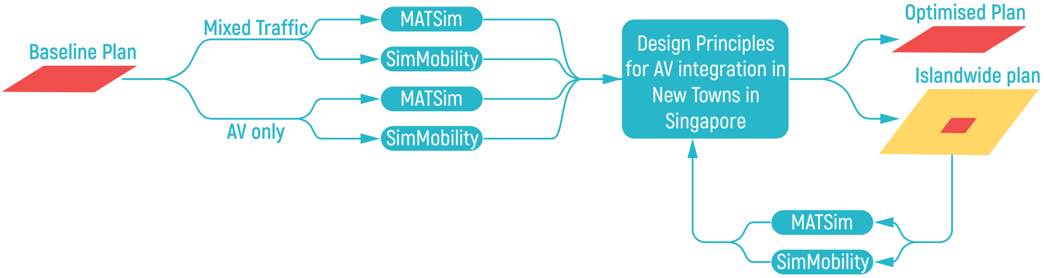
4 Dec 2018	**Y2Q3**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
12 Dec 2018	Design Review Meeting	SEC[2], URA
26 Dec 2018	Design Studio Preparation	SEC[2], URA
7 Jan 2019	Working Level Meeting 5	SEC, MIT, NUS, MoT, URA, HDB, LTA
14 Jan 2019	Design Studio Preparation	SEC[2], URA
30 Jan 2019	**Mid-term Review**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
22 Jan 2019	Briefing to MND and HDB	SEC, MIT, NUS, MND, HDB
15 Feb 2019	Design Studio	SEC[2], URA
22 Apr 2019	Working Level Meeting 6	SEC, MIT, NUS, MoT, URA, HDB, LTA
26 Apr 2019	Design Review Meeting	SEC[2], URA
8 May 2019	**Y3Q1**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
11 July 2019	**Y3Q2**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
15 July 2019	Design Review Meeting	SEC[2], URA
19 July 2019	Briefing to CARTS working Group	SEC, MIT, NUS, MoT, URA, HDB, LTA, CARTS
20 Sep 2019	Working Level Meeting 7	SEC, MIT, NUS, MoT, URA, HDB, LTA
11 Oct 2019	Design Review Meeting	SEC[2], URA
14 Oct 2019	**Y3Q3**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
13 Nov 2019	Design Review Meeting	SEC[2], URA
13 Jan 2020	Working Level Meeting	SEC, MIT, NUS, MoT, URA, HDB, LTA
13 Feb 2020	**Y3Q4**	**SEC, MIT, NUS, MoT, URA, HDB, LTA**
21 Aug 2020	Final Review Meeting	SEC, MIT, NUS, MoT, URA, HDB, LTA
6 Aug 2020	Briefing to CARTS working Group	SEC, MIT, NUS, MoT, URA, HDB, LTA, CARTS

SEC: Singapore ETH Centre (Future Cities Laboratory); MIT: MIT (SMART: Singapore-MIT Alliance for Research and Technology); NUS: National University Singapore; MoT: Ministry of Transport; URA: Urban Redevelopment Authority; HDB: Housing Development Board; LTA: Land Transport Authority; CARTS: Committee on Autonomous Road Transport for Singapore; MND: Ministry of National Development

1 – NuTonomy, World Bank and Future Cities Laboratory

2 – Author leads the meeting

Figure A 1 Workflow of the L2NIC project



Appendix 2: Design Workshops

Two half-day workshops were conducted in 2017 with all collaborators of the L2NIC project to define the parameter space and questions of interest. The first workshop focussed on defining the scope of the investigation, including the operating model of shared automated vehicles and the urban context of operation. The second workshop delved deeper into the design strategies for the technological shift and their possible implications. The discussions in the workshops contributed to the formulation of design experiments.

Workshop 1

Exploring the Operational Model and Context

The first workshop took place on 10 March 2017 in Future Cities Laboratory, Singapore. It was attended by 35 participants, of which three attended remotely through video conferencing. The workshop began a round of introductions, followed by presentations on the opportunities and constraints of the L2NIC project site. After a general discussion on the impacts of automated vehicles on urban form and transport supply, the participants broke out into three groups for a one-hour brainstorming session. Results of the break out session were shared with all participants in the final hour of the workshop.

Figure A 2 Group 3 during the brainstorming session in the first workshop.

What is an AV

The first question addressed in the workshop dealt with what an 'AV' mean in the context of this project. Is it a private car without a driver, an automated bus or a shared taxi? In Section 3.3, we discussed the four drivers of the technological shift in transportation – (1) pace of technological development, (2) operational policy and regulations, (3) public acceptance and other social factors, and (4) urban planning and design. Based on these factors, two axes of types of AV operations were identified to unpack this question, as shown in Figure A 3.

Two axes of AV operation type

The first axis is the operational context. A restricted operational context implies that the use of AVs is restricted in space, either in an 'AV-only' zone or lanes/streets. AV use may be restricted because the technology does not allow AVs to operate in all environments, or as a result of restrictive policy. The second axis is the user group. The user group could be restricted by place of residence or ability to procure a certificate of entitlement (CoE) to buy a private AV, or any user could be allowed to access an AV globally. The latter is possible when automated vehicles operate as shared taxis or buses. The two axes give four extreme operational models – the private ownership model, the restricted use model, the regulated transit fleet model and the taxi and ride-sharing model (see Figure A 4).

Private Ownership Model

In this model, any car buyer can choose between human-driven or automated cars to operate in all areas unrestricted. AVs are accessible to only those who can afford to buy a vehicle and procure a CoE for it, resulting in upgraded experience for the existing car driver, at the risk of increasing overall car ownership, as vehicles become more versatile and attractive.

Taxi and Ride-sharing Model

In this model, there are no personally owned AVs. Instead, all automated vehicles are shared and operate as taxis or DRT unrestricted on a city-wide scale. Between the more expensive private taxis and cheaper shared vehicles, users have a range of options to choose from. Such a system could be run by competing enterprises or a single operator, guaranteeing maximum efficiency but risking market monopoly. There is also a risk of an increase in VKT and instability in service levels.

Government regulated fleet

In this model, AVs operate as large vehicles in a government-managed and operated fleet of fixed-route buses. The bus routes are centrally planned, and the bus lanes are designed to be segregated from regular traffic, similar to a bus rapid transit system. The transit operator can exert more control over mode share distribution in this model.

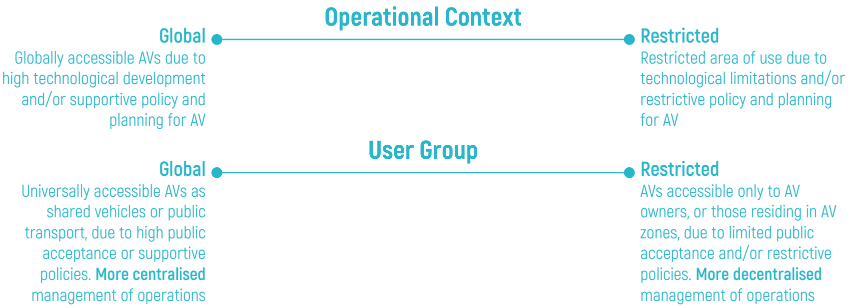
Restricted Use Model

In this model, AVs can only operate in a restricted area, pre-fitted for operation, due to lack of trust in technology, or as a mechanism to control overall VKT. The use of AVs could be restricted to closed areas, like a college campus.

It was clear that each model has its advantages and disadvantages, and no single model is a 'best-fit'. A combination of all types of services needs to be implemented in response to different urban contexts. Three types of urban contexts were selected for discussion – (1) mixed-use district, (2) residential new towns, and (3) central business district (see Figure A 5). Each group was assigned one type of development and asked to examine the type of operational models that would suit the development type.

The suitability of the operating model needs to be assessed from multiple perspectives. In chapter 3, we discussed the impacts of the technological shift on cities in five areas - traffic flow and value of time, space and space use, energy consumption, transit and active mobility and economic affordability. The finding from this literature review was shared with the workshop participants. Each group examined the impacts of the different operational models in the given urban context, based on these performance indicators.

Figure A 3 Two axes of type of AV operations



Globally accessible AVs due to high technological development and/or supportive policy and planning for AV

Restricted area of use due to technological limitations and/or restrictive policy and planning for AV

Universally accessible AVs as shared vehicles or public transport, due to high public acceptance or supportive policies. **More centralised** management of operations

AVs accessible only to AV owners, or those residing in AV zones, due to limited public acceptance and/or restrictive policies. **More decentralised** management of operations

Figure A 4 Four operational models for AVs

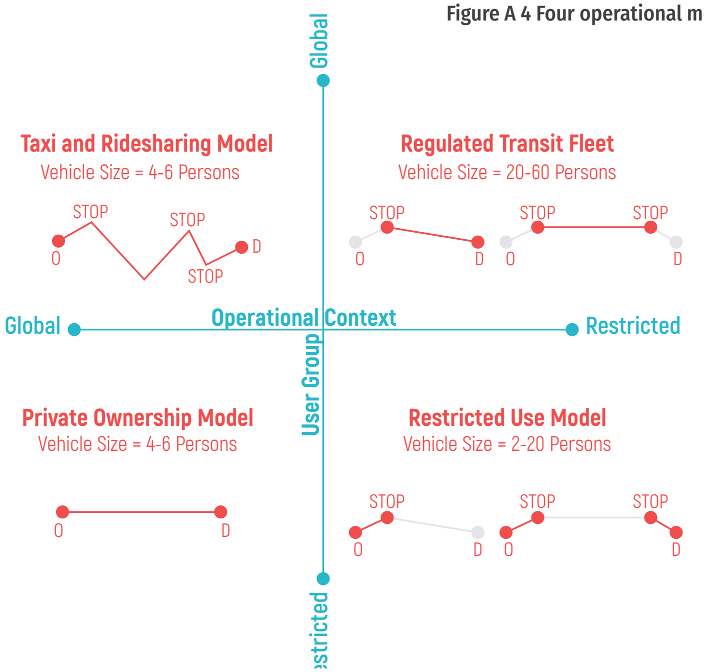
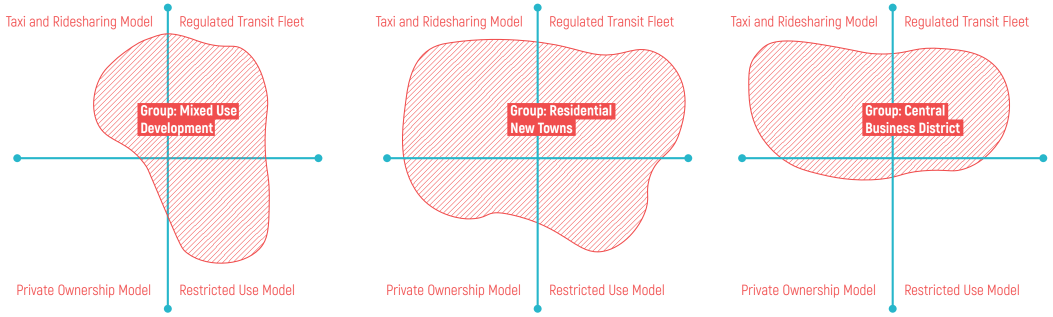


Figure A 5 Three urban development types considered for the workshop.
Source: Photos by John T, Wayne Chan, Wengang Zhai on Unsplash.com

Matching operational model to the urban context

Figure A 6 AV operating models for three urban contexts



Car-lite Goal

There was unanimous agreement in all groups on moving towards a 'car-lite' future, as a part of the Sustainable Singapore Blueprint 2015. The goal was to reduce reliance on cars and move towards public transport, cycling, walking and carsharing services. Mass Rapid Transit (MRT) of Singapore was considered the backbone of the transport network such that all new services must be designed to support it. Thus, the 'Regulated Transit Fleet' model was favoured over the rest in all groups, as shown in Figure A 6.

Operational model for mixed use

In Group 1 (Mixed-use), there were concerns raised regarding taxi and ride-sharing model affecting the mode share of regular transit service. Taxi and ride-sharing were only allowed in restricted areas to serve first and last-mile trips. Given this combination of operational models, three areas of concern emerged – street capacities, parking and freight management.

Dynamic use streets

The group proposed dynamic use streets, where the street capacity would increase during peak hours and reduce to accommodate other uses in off-peak hours. The opinion was divided on the shared use of streets, where some saw vehicle automation as an opportunity to create more lively streetscapes, and others were sceptical about the feasibility of such a design due to lack of trust in the technology.

Freight strategy

Freight traffic is one of the most important generators of transport flows in mixed-use neighbourhoods, and it was unclear how it would be handled through any of the given models. Two main strategies were suggested - creating of freight consolidation centres at an urban and neighbourhood scale, and using platoons of freight vehicles as a way to distribute the consolidated goods. It was proposed to build underground channels for the movement of these platoons.

Parking strategy

Parking was the final point of contention in the first group. An 'always cruising' strategy was suggested instead of a stationary parking lot. A mixed-use neighbourhood may generate much internal transport flows in both directions, such that a shared automated vehicle (SAV) may never need to park. An SAV could cruise at a fuel-efficient speed and position itself in an area where demand is anticipated. The upper floors of existing parking structures could be retrofitted for repair and maintenance purposes. However, there were fears regarding the increase in VKT and instability in service with this strategy.

Small vehicle platoons for new towns

Similar to Group 1, concerns were raised regarding the cannibalising of public transit and active mobility mode shares by AVs in Group 2, residential new towns. There was no consensus on a single operating model, and a spectrum of services across all quadrants was suggested instead, as shown in Figure A 6. While private vehicles and taxis could provide full trips with no transfers, thus improving the quality of the trip, a regulated fleet would be more space-efficient for longer trips. A fleet of small vehicles could combine the benefits of the two, by serving full trips as a taxi, or coupling together in a platoon to serve long-distance trips. This modularity would also address the problem of large empty vehicles during off-peak hours, common in residential neighbourhoods. The use of these vehicles could be restricted to the New Town boundary to serve first/last mile trips to public transit.

Concerns regarding PUDO

Pick-up and Drop-off (PUDO) areas for such a large fleet of small shared vehicles was a point of concern. Participants were unsure about the number and size of PUDO points needed. Some participants suggested compulsory provision of PUDO points in every residential block, while others questioned if there was enough capacity to accommodate them. Provision of more activity opportunities was also suggested in order to create a more attractive environment to walk and cycle.

Freight issues

In group 3, dealing with the central business district, a combination of taxi, ride-sharing and fixed-route transit was selected. There were three areas of concern identified – freight, pick-up/drop-off points and street capacities. As in the case of the first group, freight was a difficult issue to reconcile within the framework of the four operating models. A regional and neighbourhood freight consolidation centre was proposed to improve routing and reduce the number of empty vehicle kilometres travelled.

PUDO issues

The issue of PUDO provision raised many questions. How many PUDO points of what size would be needed? Would they be co-located with existing bus stops? Would they be more closely spaced? How would this affect the vehicle ridership? There was a lack of clarity around what the PUDO would look like in this AV integrated future business district.

Street Capacity

The final area of concern was street capacities. Streets in business districts are utilised unevenly, between weekdays and weekends and between inflow and outflow directions during peak hours. A dynamically adaptive street was proposed where the lanes would be demand responsive. Lane directions could change and reverse based on demand. During off-peak hours, the lanes could be blocked out entirely and used for other purposes.

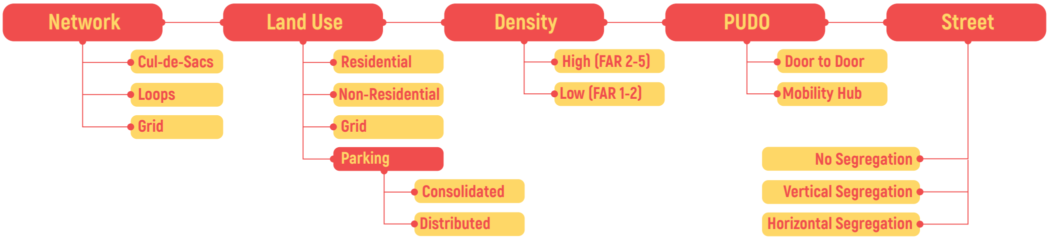
Workshop 2
Exploring the Design Strategies

The second workshop was organised on 18 July 2017, to brainstorm design implications of the four AV operational models discussed before. The half-day workshop was conducted with 40 participants from the agencies and institutes collaborating on the L2NIC project, as well as external participants from nuTonomy (a Singapore based AV start-up), World Bank and Future Cities Laboratory. The workshop began with a round of introductions and presentations on the workshop format. Thereafter, participants split into four groups of 10 persons each, including a moderator, note-taker. After the two-hour design session, all groups shared their conclusions in an open presentation.

Figure A 7 Group 2 during the brainstorming session at Workshop 2

Using Layers and Templates Method for the Design Workshop

Figure A 8 Layers and Templates given to participants in Workshop 2



A 2 X 1.5 km large site was provided as a base to test design strategies for a new residential town where all operating vehicles are automated. The given site broadly resembled a typical Singapore New Town. Half the site area was forested, and the rest was served by two MRT stations. The periphery of the site was bound by highways, separating it from low and high-density housing. The participants were asked to design a new AV integrated residential town on this site. Since this workshop heavily relied on design as a method of inquiry, each group was provided with a draughtsperson to support them. A 'layer and template' based method was used to construct these designs, as shown in Figure A 8.

In section 5.4, we discussed elements of urban form that influence transport flows, based on which, five areas of intervention were identified. These form the five 'layers' – Network, Land Use and Parking, Development Intensity (or Density), PUDO and Street Profile. Participants were asked to assemble their designs layer by layer, using a set of Singapore specific 'templates' provided. This systematised method eased design production for the participants. The Layers and Templates were organised as follows:

Network

Three types of grid templates were offered– a disconnected a cul-de-sac dominant grid, a reasonably connected loop-based grid, and a highly connected fine-grained grid.

Land Use and Parking

Four main sub-layers form the land use – residential, which are the origins of flows, non-residential (retail and offices), which are the destinations of flows, and green spaces, which may account for recreational/off-peak flows. The fourth layer, parking, has two additional templates– large consolidated parking lots or smaller distributed parking structures, similar to the current convention.

Density

While land use determines the direction of transport flow, density is a determinant of the intensity of flow. Two templates were provided for this layer – high density (Floor Area Ratio 2-5) and low density (Floor Area Ratio 1-2).

PUDO

Two templates were provided for pick-up/drop-off activity– a dedicated PUDO for door-to-door service, and an integrated mobility hub. The spacing of the PUDOs could be more frequent in the former case, and less in the latter.

Street

The street layer addresses how automated vehicles may influence the active mobility experience, and the templates determine how and to what extent will non-automated actors be segregated from the automated ones. Three templates are provided – no segregation at all (mixed traffic), vertical segregation (through bridges and underground tunnels) and horizontal segregation (either through fences and buffers between lanes, or complete separation of networks).

Participants were asked to develop these five layers for the site provided, using one quadrant to the operational model matrix (see Figure A 4) as the dominant model on their site. Once participants assembled all five layers through overlays, annotated maps, sketches and drawings, they shared it in an open forum. The points of consensus and debate were recorded by the note-takers during the discussion, which later informed the design experiments discussed in chapter 9.

How do you design a town where most people own an AV?

Figure A 9 Layers and templates for New Town with private AVs

Grid Network

A high share of privately owned AVs was assumed as a starting point for the new neighbourhood. There were two conflicting views on the network in the group. In one, more connected-ness was favoured so that cars could move more efficiently. In a second view, connected-ness was avoided in order to deter private car use, given the high private vehicle ownership rates. Two types of networks were overlaid – a large size grid network for AVs and a finer-grained grid for pedestrians and cyclists.

Density, intersections, parking

The density of development was between low to medium, and high near train stations with mixed land use and low speed limits. In order to accommodate parking space for a large number of private vehicles, either the forested areas would need to be developed, or underground parking structures would be built. The latter option was favoured by the group, but the participants were unclear about the feasibility of this option. There was some debate on whether signalised intersections were required at all if all vehicles are automated. All intersections in high-density areas were designed as non-signalised pedestrian priority crossings. In low to medium density areas, pedestrians and vehicles were separated through grade to provide seamless mobility for both.

Promote shared vehicle use

There was consensus on following a transit-oriented approach in order to reduce car ownership rates. The participants believed that even if AVs were privately owned, they would likely be used by multiple users or for multiple purposes, through social coordination. In order to promote shared use, door to door pick-up and drop-offs were discouraged.

How do you design a town where most people share rides?

Figure A 10 Layers and templates for New Town with shared AVs

Grid network

This group focussed on designing for a neighbourhood with a high share of vehicle sharing and ride-sharing. For this reason, they chose a highly connected and permeable network topology, which allows more route options. The streets were designed hierarchically, with different streets allowing different speeds and types of vehicles. Thus taxis in inner neighbourhoods run at very low speeds and speed up when they exit to main roads. In general, cars were not seen as a problem, since it was expected that the number of vehicles would be small given the high rate of sharing. Thus the focus was not on limiting car use but promoting connectivity for all.

Density, parking

Similar to the first group, high-density mixed-use development was concentrated near the transit stations, and the remaining area was designed as low-density residential development. Parking for all shared vehicles was consolidated and moved to two underground lots on the periphery of the site. The two parking areas would accommodate about 600 vehicles in total. The was calculated based on the assumed peak hour demand for 40,000 people, of which half would be served by feeder taxis for the MRT. This allowed the group to not only retain the existing forested area but also provide more recreational green spaces within site.

Two types of PUDO

The type of interface for access was dependent on the development intensity. Consolidated neighbourhood pickup points were provided for high-density areas and while door-to-door pick-up facilities were provided in low-density areas. Taxi drop-off points were tightly integrated with MRT stations to minimise transfer time.

How do you design a Town where most people use public transit?

Figure A 11 Layers and templates for New Town with automated public transit

Loops Network

This group worked with an entirely automated fixed-route transit service as the dominant mode of transport. A moderately connected network with loops was selected first since the loops would be ideal for accommodating high-speed transit corridors. Some concerns were raised regarding the creation of congestion at intersections due to this network topology. The participants also saw conflict between fixed-route long-distance AVs and automated DRT as a feeder system for the MRT. The transit system adopted for the site was a combination of larger fixed-route shuttles and smaller dynamically routed vehicles that would serve first/last mile trips.

High density

High-density development type was adopted for a large part of the site, to maximise the efficiency of public transit and minimise the transit stops needed. All non-residential facilities, such as shops and hospitals, were provided near the transit stations. This freed up more land to create parks and greenways that could double up as active mobility corridors.

Door to door PUDO

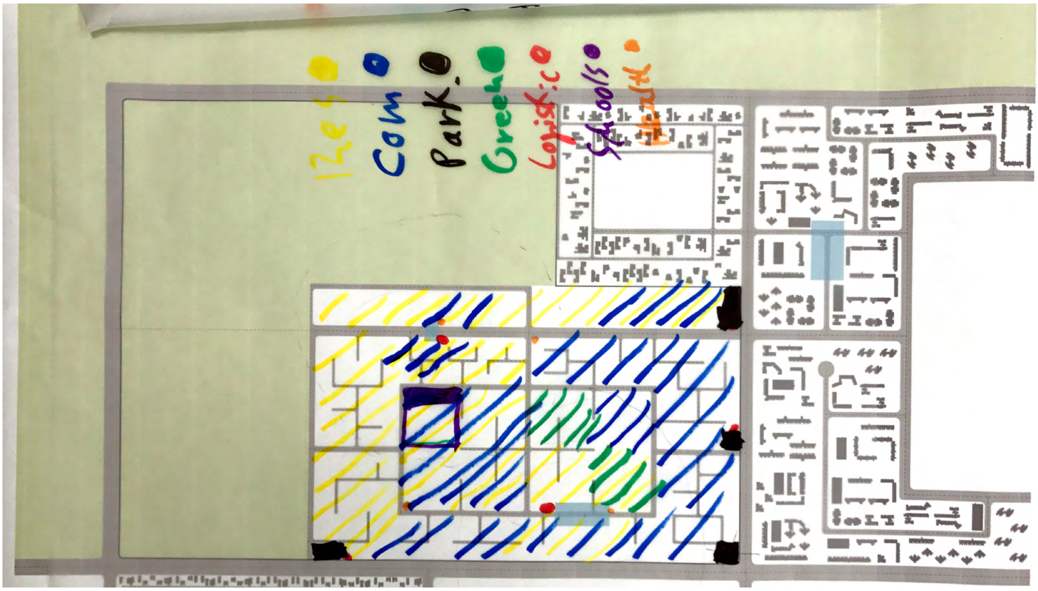
In order to be competitive with private cars and taxis, DRT service could be accessed through a pick-up lobby in every residential building. Parking lots, on the other hand, were provided further away than PUDO points, in order to make access to DRT easier than private cars. Consolidated parking clusters were favoured over distributed lots.

Street segregation

The level of mixing between AVs and non-automated actors on the street was linked to the speed limits. Low-speed streets were highly mixed, and high-speed streets had strong physical segregation between AVs and the rest of the traffic. These streets also functioned as high-speed bus rapid transit corridors with minimum conflicts and crossings.

How do you design a town where AVs pods are last-mile feeders?

Figure A 12 Layers and templates for New Town with last-mile feeder AVs



Cul-de-sac Network

The service area of the AVs was restricted to the given site, and anyone entering or exiting the site would have to switch to an AV pod, and vice versa, which would require the provision of special PUDO infrastructure. The group selected a large grid with cul-de-sacs as the preferred network topology since this is the most common topology found in New Towns. The network structure is not public transport friendly, due to the narrow inner streets and many U-turns, but suitable for small and agile AVs are more efficient than a lumbering bus.

Land use, streets

Land use distribution in this design was reasonably mono-functional, with commercial areas concentrated near transit hubs. Assuming centralised control of AVs, it would be possible to have a dynamic network where the number of lanes in each direction would change according to demand, to accommodate unidirectional peak hour traffic. If no private vehicles are allowed in the network, it would be easier to optimise the performance of such a network. The group believed that the accessibility benefits of AVs need not be accompanied by an increase in density since there are various stresses associated with high-density living. Medium-density development was distributed evenly across the site with slightly higher densities permitted around MRT stations.

Two types of PUDO

A two-tiered access system for AVs was proposed – consolidated neighbourhood pick up point and door to door service. While in group 2, density was used as a criterion for selection of PUDO system, in this group, door-to-door service was envisioned as a paid premium service. Accessing the AVs from a 'bus top' like consolidated PUDO would be much cheaper than door-to-door service. The pricing of this service will be different for vulnerable and off-peak users. Participants were uncertain about the size of these consolidated PUDO points, based on the demand by time of day.

Commonalities and Conflicts

Commonalities and points of consensus

All four designs had certain commonalities and point of contention. There was general agreement across all groups on vehicle types, density and integration of active mobility infrastructure. Smaller agile vehicles were preferred, which would operate as demand responsive transit (DRT). The density fluctuated between medium to high, given the need to accommodate new development while maintaining existing green areas and maximise the efficiency of public transit or ride-sharing systems. All groups also provided a dedicated network for active mobility, which either coincided with the traffic network but was separated from it through a physical barrier, or designed as an entirely separate network layer.

Points of contention

The main points of debate were the design of intersections, PUDO, parking and network. While some participants preferred complete physical separation between AVs and other traffic at intersections, others were sceptical about the impact of this strategy on walkability. There was also a lack of clarity around the optimal size and location of PUDO points and parking. For example, while some participants advocated building underground parking structures, it was difficult to determine its feasibility, if the total vehicle stock is unknown. The selection of network topology design was contingent on the type of operating model, land use distribution and intended mode share. Each group presented arguments for and against all three network types in relation to different transportation goals.