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Examination and Analysis of Complex Public-Transport Networks

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A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy in Civil Engineering

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Abstract

The main function of public transport (PT) is to serve society. As such PT should provide users with a reliable, high-frequency, accessible, comfortable and well-coordinated service. Nowadays, due to factors such as the growth of modern cities leading to an increased level of vehicular traffic and congestion, PT service has been continuously experiencing problems harming its image and attractiveness: non-regular vehicle arrivals at PT stops and missed buses leading to increased waiting times. On the other hand, PT operators seek to make the service efficient and reduce operating costs through measures such as limited coverage comprising a small number of direct routes with a reduced fleet size and low frequency of service. Such measures directly influence passengers who need to perform more transfers between routes. The inconvenience of making transfers accompanied by extended waiting times coupled with the observed delays of arriving vehicles at transfer stations leads to missed transfers and increased waiting times, which impact the quality of PT service and makes PT less attractive.

This doctoral research project is aimed at finding a solution to the above problem through providing PT users with a reliable, punctual, fast and convenient service which makes trips for current and prospective users within the network of PT routes more convenient and shorter in time—an intent implemented through designing a public-transport network (PTN) and performing multi-agent simulations of the passengers’ transportation process along the routes within the whole network, on a case study.

The above was achieved in a sequence of steps including:

(i) Development and application of a method combining computer programming, statistical data and large-scale network analyses, allowing examination of the structure of public transport networks (PTNs) and analysis of their topological properties. The method was applied on two real-life case studies comprising the public transport bus network in Auckland (New Zealand) as a first case study presented in Chapter 2 and as a second case study of the subway PTNs at Washington DC (USA) and Oslo (Norway) presented in Chapter 3. It was found in Chapter 2 that the examined bus-route network of Auckland is not scale free nor does it exhibit all the features of “small-world” networks. Instead, it can be considered as a mixture of exponential and scale-free networks, which means that the evolution of the bus route network in Auckland is a consequence of random rather than preferential attachment of newly opened stops. The network analysis performed in exploring the topological properties of the Washington DC and the Oslo metro networks documented in Chapter 3 showed that when represented in an L-space network topology, the examined networks do not exhibit small-world properties, and hence, they are not small-world networks. The examination of the Washington DC metro network and its analyses also showed that the network is neither a scale-free nor random network; this is based on the consideration of the network’s node degree distribution, the number of the metro lines servicing each station and representing the network as a bus station network. In contrast to the Oslo metro
network, the metro network in Washington appears to be a complex network. The analysis considering the networks’ global efficiency, performed by using network science concepts and findings, showed that both the metro networks examined have low valued global network efficiencies and therefore appear not to be fault tolerant.

(ii) Modelling the interaction between passengers, buses and cars along a route of PTN (on a case study in Auckland) as a small-scale multi-agent system (MAS) which facilitated establishing the influence of PT demand on passenger waiting time at bus stops when using vehicles in scenarios providing different passenger capacity and frequency of service. The simulation output results in Chapter 4 demonstrate that when PT demand is less than bus capacity, that capacity does not affect the average waiting time at bus stops. In cases where PT demand is high, high bus capacity resulting in an increased number of passengers boarding the bus, indirectly causes increased passenger waiting times, unless the frequency of service is increased. These results could serve PT operators well in the trade-off situation when choosing between increased bus frequencies and larger size bus capacities, especially when the PT demand at bus stops is high.

(iii) Developing a simulation framework and a model providing the options to model a high-frequency, metro-like, autonomous PT service. The results obtained from the implementation of the developed simulation model, which was calibrated and validated on a numerical example under different simulation scenarios depicted in Chapter 5, showed that the model satisfactorily reproduces the parameters of the modelled system: (a) Among the scenarios, scenario 4 simulating a high frequency, metro-like PT service, due to small vehicle headways, provides passengers with the least average waiting time at bus stops; (b) Due to the small capacity of the high frequency vehicles used, which means less time for boarding/alighting (in contrast to the large-vehicle scenario), scenario 4 offers the lowest estimated average dwell time accumulated along the whole PT line; (c) The high frequency public-transit service provided in scenario 4 is the one that provides the least number of unserved passengers along the route of the modelled PT line; (d) A small decrease in the frequency of the vehicles (less vehicles) when a high frequency, metro-like service is provided, leads to an improved utilisation of vehicle capacity (operator’s perspective) at the cost of an acceptable increase of the average passenger waiting time at bus stops (user’s perspective) and insignificant increase in the number of unserved passengers.

(iv) An application on a case study of the agent-based modelling concept in designing a MAS with interacting agents, such as PT users, self-driving vehicles and network sections, and performing multi-agent simulations of the passengers’ transportation process along the routes of a newly-designed public transport network having a specific topology and features (considered from network science’s perspective), aimed to examine, analyse and improve the modelled system. The results of the simulations in Chapter 6 reveal the potential of the proposed monorail public transport network with driverless operating vehicles in achieving an attractive, reliable, punctual and fast public transport service.
Dedication

"It doesn't matter how slowly you go as long as you don't stop."

~ Confucius

To my lovely wife Denitsa who has always been with me over the years to support me in the hard moments along all the way of this challenging and exciting journey, as well as to our precious and sunny children – Boris and Bozhidar – who are my inspiration and whose smiles and warmth motivate me and give me the strength to get up day after day and keep going...
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➢ my lovely wife, Denitsa, who was behind me all the time. Thank you very much, my love, for your patience and tireless support over the long days and sleepless nights. Thank you also for teaching me how to look at things from different perspectives and showing me how to be a good husband and mindful father of our lovely children. Your endless love and sunny smile helped me to realise my potential, overcome any obstacles along the way, go beyond barriers and never give up…

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➢ my best friends – Bozhidar, Ventsislav and Vladimir – for their patience and understanding and for never forgetting me regardless of the distance between us.

“It always seems impossible until it’s done.”

~ Nelson Mandela
Publications

As the present PhD thesis is paper-based, some of the chapters in it contain text from published articles or from papers submitted for publishing both containing some minor changes or supplements that have enriched the thesis’s content as well as some minor changes in the numbers of tables, figures, charts, and others, with which a better clarity was achieved.

Chapter 2:


Chapter 3:


Chapter 4:


Chapter 5:

# Table of Contents

**CHAPTER 1. INTRODUCTION** ........................................................................................................... 1

1.1 Research problem ......................................................................................................................... 1

1.2 Objective of the PhD thesis ........................................................................................................ 3

1.3 Tasks of the doctoral research project ......................................................................................... 3

1.4 Scope and stages of the research methodology ..................................................................... 4

1.5 Significance of the research ...................................................................................................... 7

1.6 Intended research contributions of the thesis ....................................................................... 8

1.7 Thesis structure ......................................................................................................................... 9

**CHAPTER 2. A METHOD OF EXAMINING THE STRUCTURE AND TOPOLOGICAL PROPERTIES OF PUBLIC-TRANSPORT NETWORKS** ............................................................................. 12

2.1 Objectives ................................................................................................................................. 12

2.2 Literature review: Examination of complex networks ....................................................... 12

2.3 Method ................................................................................................................................... 21

2.4 Case study ................................................................................................................................ 29

2.4.1 Data Collection .................................................................................................................... 29

2.4.2 Data processing .................................................................................................................... 30

2.4.3 Examining PTN for scale-free characteristics ................................................................. 31

2.4.4 Examining PTN for “small-world” properties ................................................................. 33

2.5 Conclusions .............................................................................................................................. 35

**CHAPTER 3. STRUCTURE AND TOPOLOGICAL PROPERTIES OF PUBLIC-TRANSPORT NETWORKS USING NETWORK-SCIENCE CONCEPTS: A CASE STUDY** ......................................................... 37

3.1 Objectives and tasks of the case study ...................................................................................... 38

3.2 Literature review ....................................................................................................................... 38

3.3 Case study ................................................................................................................................ 42

3.3.1 Data collection and data processing .................................................................................. 42

3.3.2 Examining the subway network for small world properties ........................................ 43

3.3.3 Examining the subway network for scale-free properties ............................................. 52

3.4 Conclusion ................................................................................................................................. 56

**CHAPTER 4. MODELING THE INTERACTION BETWEEN BUSES, PASSENGERS AND CARS ON A BUS ROUTE USING A MULTI-AGENT SYSTEM** ............................................................................. 58

4.1 Significance of the research ...................................................................................................... 58

4.2 Scope and objectives of the research ...................................................................................... 59

4.3 Literature review ....................................................................................................................... 59

4.3.1 Public transit improvements ............................................................................................. 59

4.3.2 MAS and public transit ..................................................................................................... 60

4.4 Methodology ............................................................................................................................ 62

4.5 Case study ................................................................................................................................ 63

4.5.1 Data collection, processing and analysis ......................................................................... 63

4.5.2 Modeling the MAS ........................................................................................................... 66

4.5.3 Simulation model – calibration and validation ............................................................... 69

4.6 Conclusions ............................................................................................................................... 79
LIST OF TABLES

Table 2.1. Derived regression equations with their estimated parameters .......................................................... 32
Table 2.2. BRN in Auckland compared to random network generated with Pajek .................................................. 34
Table 3.1. Washington DC’s metro network compared with a random network generated with the Pajek program .... 48
Table 3.2. Oslo’s metro network compared with a random network generated with the Pajek program ............. 48
Table 3.3. Derived regression equations with their estimated parameters for the metro network in Washington describing the probability distribution of Washington’s DC metro stations in function of the number of metro lines k servicing a station .................................................................................................................. 54
Table 3.4. Derived regression equations with their estimated parameters for the metro network in Oslo describing the probability distribution of Oslo’s metro stations in function of the number of metro lines k servicing a station ............. 54
Table 4.1. Input parameters ............................................................................................................................ 69
Table 4.2. Experimental capacities and frequencies. ......................................................................................... 74
Table 5.1. Passenger demand at bus stops (boarding/alighting passengers) ...................................................... 96
Table 5.2. Scenarios played (Direction: From bus stop 1 to bus stop 6) .............................................................. 101
Table 5.3. Scenario 4: 30 vehicles with capacity of 40 passengers going along the route with a 2.0-minute headway. 104
Table 5.4. Scenario 4.1: 24 vehicles with capacity of 40 passengers going along the route with a 2.5-minute headway ............................................................................................................................................ 104
Table 5.5. Summary of the results for the performed two-tailed t-test for statistical significance of the slope with accepted significance level \( \alpha = 0.05 \) and calculated degrees of freedom \( df = 3 \) ............................................................................. 108
Table 6.1. Monorail stations, sections’ lengths and calculated in-vehicle travel times ........................................ 130
Table 6.2. Monorail stations, sections’ lengths and calculated in-vehicle travel times ........................................ 130
Table 6.3. Monorail stations, sections’ lengths and calculated in-vehicle travel times ........................................ 130
Table 6.4. PT O-D travel demand matrix .......................................................................................................... 131
Table 6.5. Routes along the monorail PT Lines in each of the directions .......................................................... 134
Table 6.6. Correspondence between the monorail PT stop/station numbers and the PT stop Ids in the MATSim’s PT routes ........................................................................................................................................ 134
Table 7.1. Summary of the findings, results and conclusions ............................................................................. 143
LIST OF FIGURES

Figure 1.1. Connection between the separate components constituting the PhD thesis ...........................................5
Figure 1.2. Stages of the research methodology ........................................................................................................6
Figure 1.3. Structure of the doctoral thesis ..................................................................................................................11
Figure 2.1. Random rewiring procedure of the Watts-Strogatz model (Watts & Strogatz, 1998) ....................................13
Figure 2.2. Complex networks (l.-r.): (a) “Small-World”, (b) Scale-Free and (c) Random. Adapted from (Huang, Sun & Lin, 2005) ........................................14
Figure 2.3. An example of highway (a) and airline (b) transportation systems (Barabási, 2002) .................................15
Figure 2.4. Explanation of (a) the L-space and (b) the P-space network topologies (Sienkiewicz & Holyst, 2005) .......17
Figure 2.5. PT Networks (Lu & Shi, 2007) .................................................................................................................18
Figure 2.6. PT network topologies (Derrible & Kennedy, 2011) ..................................................................................19
Figure 2.7. Flow-chart representing the sequence of steps outlining the logic of the proposed method ........................21
Figure 2.8. Example of PT line served by two different routes ...................................................................................22
Figure 2.9. Example of PT route-network ..................................................................................................................25
Figure 2.10. Configuration of the example PT route-network (variant 2) .................................................................28
Figure 2.11. (a) Map of Auckland (Auckland Transport. Central guide, 2014a); (b) Schematic Auckland’s PT network using TransCAD (Caliper Corporation, 2013) .................................................................30
Figure 2.12. Relative frequencies P(k) of stops as a function of the number of lines k servicing each stop ...............32
Figure 2.13. Auckland’s PT route network (all modes) as represented with Pajek ........................................................33
Figure 3.1. Washington DC Metro system map ...........................................................................................................44
Figure 3.2. Oslo Metro system map ..........................................................................................................................45
Figure 3.3. Flowchart representing the sequence of steps outlining the logic of the proposed approach for examining and analysing PT (subway/metro) networks .........................................................46
Figure 3.4. Washing DC’s metro network compared with a random network ..............................................................48
Figure 3.5. Oslo metro network compared with a random network ..............................................................................48
Figure 3.6. Distribution of the Washington DC metro stations according to the number of lines k servicing a station ...............................................................53
Figure 3.7. Distribution of the Oslo’s metro stations according to the number of lines k servicing a station ............53
Figure 3.8. Probability distribution of Washington’s DC metro stations according to the number of metro lines k servicing a station ................................................................................................55
Figure 3.9. Probability distribution of Oslo’s metro stations according to the number of metro lines k servicing a station ..................................................................................................................55
Figure 4.1. Route serving bus line number 277 (Google, 2015) ..................................................................................64
Figure 4.2. Comparison of days with highest passenger loads in direction (a) Britomart→Waikowhai and (b) Waikowhai→Britomart .............................................................................................................66
Figure 4.3. Interactions between the agents in the MAS ..............................................................................................67
Figure 4.4. Scheme of the simulation model ................................................................................................................69
Figure 4.5. Linear regression in directions B→W (a) and W→B (b). (a) Actual vs. simulated passenger loads in direction B→W; (b) actual vs. simulated passenger loads in direction W→B ........................................73
Figure 4.6. Comparison of actual vs. simulated passenger loads in 2014 and 2024 in direction B→W (a, b) and W→B (c, d), respectively ...................................................................................................75
Figure 4.6. Continued................................................................. 76
Figure 4.7. Average passenger waiting time as a result of constant bus frequency and variable capacity in direction B→W (a) and W→B (b) as well as average passenger waiting time as a result of constant bus capacity and different frequency in direction B→W (c) and W→B (d).......................... 78
Figure 5.1. Illustrative scheme of the simulation model................................................................. 91
Figure 5.2. Flowchart of the modelling algorithm of the simulation model........................................ 92
Figure 5.3. Number of the passengers boarding/alighting the bus along the route during the simulated period of time 96
Figure 5.4. Total observed and simulated passengers who alighted at each bus stop in scenarios 1-4 ((a)-(d), respectively).................................................................................................................. 99
Figure 5.5. Average passenger waiting times at the bus stops along the route.................................. 100
Figure 5.6. Relationship between simulated average waiting time and vehicles' frequency .................. 102
Figure 5.7. Relationship between dwell time and vehicles' passenger capacity.................................... 102
Figure 5.8. Number of the passengers who have not been served by the end of the simulation............. 103
Figure 5.9. Maximum vehicle capacity utilisation reached by vehicles along the bus route (scenario 4) .... 104
Figure 5.10. Maximum vehicle capacity utilisation reached by vehicles along the bus route (scenario 4.1) .... 105
Figure 5.11. Passenger load by sections along the route for vehicle # 7 (scenario 4)............................... 105
Figure 5.12. Passenger load by sections along the route for vehicle # 3 (scenario 4.1)......................... 106
Figure 5.13. Observed versus simulated passengers who alighted the bus in scenarios 1-4 ((a)-(d), respectively)...... 108
Figure 6.1. MAS-Based Public Transit System (Hadas & Ceder, 2008).............................................. 117
Figure 6.2. Generated networks by using Pajek: (a) Regular lattice and (b) Small-world network ............ 122
Figure 6.3. Illustration of the structure of the prospective network.................................................... 123
Figure 6.4. Illustration of the structure of the designed prospective monorail public transport network........ 125
Figure 6.5. Lines within the designed monorail PTN: (a) Line 1, (b) Line 2 and (c) Line 3 ....................... 125
Figure 6.6. Visualisation within Via of the designed by using JOSM network represented by nodes and connecting links ................................................................. 128
Figure 6.7. Visualisation within Via of the designed by using JOSM monorail public transport network represented by connecting route sections and stations created in MATSim ................................................................. 129
Figure 6.8. Screenshot 1 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:16:24................................................................. 132
Figure 6.9. Screenshot 2 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:18:37................................................................. 132
Figure 6.10. Screenshot 3 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:20:19................................................................. 133
Figure 6.11. Screenshot 4 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:21:17................................................................. 134
Figure 6.12. Train loads along route s1r1TOs1r4 servicing monorail Line 1 in right direction .................. 136
Figure 6.13. Train loads along route s1o1TOs1o4 servicing monorail Line 1 in opposite direction............ 137
Figure 6.14. Passengers carried between the stops along route s1o1TOs1o4 servicing monorail Line 1 in opposite direction by the train departing station s1o1 at 07:20 ................................................................. 137
Figure 6.15. Passengers carried between the stops along route s1o1TOs1o4 servicing monorail Line 1 in opposite direction by the train departing station s1o1 at 07:35 ................................................................. 138
Figure 7.1. Flow-chart of the main findings and conclusions.............................................................. 147
# LIST OF ABBREVIATIONS, ACRONYMS AND TERMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Albert’s growth model</td>
</tr>
<tr>
<td>ABM</td>
<td>Agent-Based Modeling</td>
</tr>
<tr>
<td>ABMS</td>
<td>Agent-Based Modeling and Simulation</td>
</tr>
<tr>
<td>ADT</td>
<td>Average Dwell Time</td>
</tr>
<tr>
<td>ANND</td>
<td>Average Network Node Degree</td>
</tr>
<tr>
<td>APL</td>
<td>Average (Network’s Shortest) Path Length</td>
</tr>
<tr>
<td>ATTT</td>
<td>Average Total Travel Time</td>
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<tr>
<td>B</td>
<td>Barabási’s preferential attachment model</td>
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<td>BA</td>
<td>Barabási-Albert model</td>
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<tr>
<td>BRN</td>
<td>Bus-Route Network</td>
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<tr>
<td>BRT</td>
<td>Bus Rapid Transit</td>
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<tr>
<td>BSN</td>
<td>Bus Station Network</td>
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<tr>
<td>BTN</td>
<td>Bus Transportation Network</td>
</tr>
<tr>
<td>CBD</td>
<td>Central Business District</td>
</tr>
<tr>
<td>CC</td>
<td>(Average) Clustering Coefficient (of a network)</td>
</tr>
<tr>
<td>DE</td>
<td>Discrete-Event</td>
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<tr>
<td>ER</td>
<td>Erdős-Rényi</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>GPSS</td>
<td>General Purpose Simulation System</td>
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<tr>
<td>GTFS</td>
<td>General Transit Feed Specification</td>
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<tr>
<td>MAS</td>
<td>Multi-Agent System</td>
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<tr>
<td>MATSim</td>
<td>Multi-Agent Transportation Simulation</td>
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<tr>
<td>MMNDP</td>
<td>Multimodal Network Design Problem</td>
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NDD – Node-Degree Distribution
NS – Network Science
O-D – Origin-Destination
OMN – Oslo Metro Network
PLUS – Programming Language Under Simulation
PT – Public Transport
PTN(s) – Public-Transport Network(s)
PTP – Passengers Transit Process
PTRN – Public Transportation Route Network
PTTN – Public Transportation Transfer Network
RN(s) – Random Networks(s)
SFN(s) – Scale-Free Network(s)
SPSS – Statistical Package for the Social Sciences
SWN(s) – “Small-World” Network(s)
TIVTT – Total In-Vehicle Travel Time
TNDP – Transit Network Design Problem
WMATA – Washington Metropolitan Area Transit Authority
WMN – Washington Metro Network
WS – Watts and Strogatz
WWW – World-Wide Web
Both the terms “Agent-based model” (or “Agent-based modelling”) and “Multi-agent simulation” are used with different meanings in this PhD thesis.

The terms “Agent-based model(s)” and “Agent-based modelling” are used within separate parts and chapters of the thesis including the Abstract, section “1.1 Research problem”, section “1.3 Tasks of the doctoral research project”, in Chapter 4 comprising the literature review as well as the case considering the interaction between the agents buses, passengers and cars along a single bus route. These terms are also used in the literature review of research works in Chapter 6 in the thesis when discussing agent-based modelling as a modelling approach and the practical application of agent-based models and software platforms representing the interaction of multiple actors called agents as opposed (or as an alternative) to the other existing models. Another example for the usage of the term “agent-based model” is in Chapter 6 when discussing MATSim (Multi-Agent Transport Simulation) – a large-scale, Java-based, agent-based traffic simulator implementing the agent-based modelling concept (paradigm).

The term “Multi-agent simulation” is used when discussing (mainly in Chapter 6) simulations of the passengers’ transportation process along the routes within a MAS – the newly-designed monorail train public-transport network.
LIST OF SYMBOLS

AWT  – Average Waiting Time

AWT_{min}  – the minimum time (in seconds) passengers wait the vehicle at the bus stop

AWT_{max}  – the maximum time (in seconds) passengers spend waiting when they arrive at the stop at the moment the bus departs the stop

AR_{OD}  – Average sequence of routes available in the network for an origin-destination (O-D) pair using the shortest O-D path

AR_{OD,d}  – Average number of routes required to cover the PT O-D demand, given O-D data

AS_{P}  – Number of sections/stops along the average shortest path across all shortest O-D paths P in the network

AS_{P,d}  – Average shortest path computed as a weighted average sum of the PT demand d_{i,j} and the shortest paths S_{P_{i,j}} between pairs of nodes i and j (expressed in number of sections)

AS_{R}  – Average number of sections/stops per individual route

C_{tr}  – Transfer Coefficient

d_{i,j}  – O-D demand between any pair of nodes i and j (for i ≠ j) in the O-D demand matrix D

d_{t}, d_{d}, d_{tr}  – Total PT O-D demand; demand covered by direct routes, and PT O-D demand not covered by direct routes, i.e., demand requiring O-D trips including transfers

H  – vehicle (bus) headway

n  – Number of vertices (stops) in the PT route-network

N_{tr}  – Number of transfers along the trips chain satisfying the PT O-D demand between any two nodes in the route network that are not accessible through direct routes

S_{d_{tr}}  – Share of the unsatisfied PT O-D demand (requiring trips with transfers)

S_{P_{i,j}}  – Shortest path between nodes i and j measured with number of sections
Co-Authorship Form

This form is to accompany the submission of any PhD that contains published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Acknowledgements. Co-authored works may be included in a thesis if the candidate has written all or the majority of the text and had their contribution confirmed by all co-authors as not less than 65%.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

**Chapter 2:**

**Nature of contribution by PhD candidate**
Designed the research framework and outlined the scope and the objective of the research, created the method, developed the computer programs, processed the data, performed statistical data and network analyses as well as structured and wrote the whole paper.

**Extent of contribution by PhD candidate (%)** 90

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<th>Name</th>
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**Certification by Co-Authors**

The undersigned hereby certify that:
- the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

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Chapter 3:

Nature of contribution by PhD candidate: Designed the research framework and problem-solving approach, developed the software programs implementing algorithms and applied these programs in computations. Performed network and data analysis as well as structured and wrote the whole paper.

 Extent of contribution by PhD candidate (%): 80

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Chapter 4:


Nature of contribution by PhD candidate

Outlined the scope and the objectives of the research. Designed the simulation modeling framework, selected the problem-solving approach as well as the modelling and simulation software products implementing the chosen simulation approach. Participated in shaping the simulation scenarios and provided guidance on how to perform the simulations. Performed post-simulation analyses as well as structured and wrote the whole paper.

Extent of contribution by PhD candidate (%)

70

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<td>Assisted in (i) data collection, data entry, data processing and visualisation; (ii) reviewing research-related papers; (iii) model creation, calibration and simulations performed; (iv) analysing results of the case study; (v) presenting the paper on the Transportation Research Board 95th Annual Meeting.</td>
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**Chapter 5:**


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Chapter 5:
http://jmmjournals.com/journals/mm/2018/2/73

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CHAPTER 1. INTRODUCTION

In the real world, especially in the 21st century, life has become very dynamic. This is highly expressed in modern towns which nowadays attract labour due to the endless job opportunities. The concentration of the labour force leads to a quick expansion of towns and their population. Due to the increased area, the distance to work inevitably increases as the traffic congestion levels do. To go from home to work people need a reliable, frequent, convenient mode of transport that is capable of satisfying their requirements and transport needs with less transfers. Servicing an increased number of direct trips requires a high frequency service provided by more vehicles running along longer routes, which would possibly lead to more operating costs incurred by operators due to increased vehicle-kilometres travelled by their vehicles. This means that operators would be interested to provide their users with shorter trips that usually result in the need for the passengers to make transfers. Transfers are accompanied by some inconveniences. Sometimes the changed travel conditions and high levels of traffic congestion may incur huge delays of PT vehicles leading to missed transfers. The latter, coupled with a non-regular PT service with a low frequency and/or insufficient capacity of vehicles, usually results in additional waiting times for passengers at regular and interchange stations and hence in an increase in total passenger travel times. Therefore, in order to be competitive against private cars and more attractive for its users, public transport (PT) must offer passengers a reliable (on time), frequent (more often), fast (in comparison to cars), convenient, accessible (within walking distance) and affordable (in terms of money) transport service: providing passengers with transport supply that meets the existing passenger PT transport demand. To be able to instantly react and adequately respond to PT demand, transport agencies and transport operators should be flexible enough in designing and developing sound PT networks with routes providing more direct trips (with less transfers) serviced by vehicles running with high-frequency a having enough passenger capacity.

1.1 Research problem

The limitations of the existing approaches, methods and tools in exploring and analysing complex real-life networks, such as PTNs, place in front of researchers and scholars lots of challenges related to data collection and processing, an application of methods and use of specialised software. Fortunately, the application of network science theory, which comprises findings in other research fields, enables to explore, model and simulate complex networks – a solid foundation for practical studies directed in examining and analysing the structure of real-world PTNs and evaluating their topological features.

The lack of a wholistic approach overcoming the data constraints and limitations of the known approaches in exploring complex public-transport networks requires development of a new tool – a
method – utilising the network science concepts and enabling examining and analysing networks, and evaluating networks’ topological properties. The application of such a method could potentially allow to identify the type of the studied networks and locate structural weaknesses and vulnerability. The latter could serve as a starting point in designing networks characterised with specific topology (considered on a structural level) – a good foundation in modelling passengers’ transportation process along the routes of a PTN (considered on a route and operational levels).

Unfortunately, from the large variety of existing models, there are models that are unnecessarily complex and/or include many input variables, which makes hard the process of finding data to feed the model and apply it on practice without using computing software and tools. On the other hand, there are models that have been developed with specialised software products that are expensive to attain and takes a long time to learn and build even relatively simple models, which may also require some programming skills. There exist also simplified models that are easy to use but do not describe the system in detail and therefore cannot give accurate results. Last, but not least are those transport models which due to features such as town architecture, road infrastructure, route characteristics, could be only applied in specific areas and under specific transport conditions. Hence, such models are not universal and neither they can be directly applied somewhere else nor they can be easily adapted with minimum modifications.

In order to realistically reproduce the processes in the studied system, models should be able to simulate the interaction of all the parties involved. The agent-based modelling appears to be an appropriate and very powerful approach enabling modelling complex systems and representing them as composed of numerous autonomous agents interacting with each other within the system’s environment, playing various roles and being able to learn and adapt.

The practical application of the agent-based modelling paradigm in creating models is accompanied with some inconveniences: (i) agent-based models require significant volumes of data which in turn requires more computational power and speed in terms of computer processor unit (CPU) and computer memory (RAM); (ii) since sometimes agent-based models are applied in modelling dynamics of new or unexplored systems, some difficulties with their validation may also arise.

Fortunately, the tremendous progress in the domain of information technologies as well as in computer hardware and software revealed opportunities to overcome the above shortcomings. Today, along with the conventional computer programming languages there is a large variety of open-source software and proprietary agent-based modelling platforms, packages and tools providing opportunities to design, model as a MAS, explore and analyse complex systems.
The above necessitates developing a research methodology which considers the “whole picture” (an entire public-transport network rather than separate routes). By means of an application of the agent-based modelling concept and making use of modern MAS platforms which perform fast simulations with interacting actors (such as passenger agents, vehicle agents, and road sections), the proposed methodology should be capable of enabling the design of public-transport networks and the simulation of the passengers’ transportation process along the routes within a whole PT network, which would provide as a result PT users with a reliable, regular and fast public transport service that meets the existing PT demand.

1.2 Objective of the PhD thesis

The objective of this doctoral research project is to simulate the passengers’ transportation process along the routes of a newly designed public-transport network as a multi-agent system composed of interacting agents and establish operational control at connection points to provide PT users with a reliable, punctual, fast and convenient public transport service.

1.3 Tasks of the doctoral research project

The achievement of the above objective raised the need to conduct a deep literature review in the following directions and solve the following main tasks:

1. Conduct a literature review of research works related to examining and analysing complex networks, including public transport networks.

2. Develop a novel and efficient method, coupled with a software tool, allowing automated extraction and processing of data, which enables examining and analysing the structure and topological properties of public transport networks (PTNs) and evaluating networks’ efficiency.

3. Practically apply the developed method on a real-world case study aimed at exploring and analysing the structure of existing PTNs, revealing statistical relationships and providing recommendations for network improvement.

4. Extend the developed method utilising network science (NS) concepts and tools and apply the proposed method on real-life case studies with the purpose of exploring the structure of PTNs, analysing networks’ topological properties, evaluating the efficiency of the studied networks and outlining directions for network improvement on a route and network level.

5. Review books and research works such as scientific articles, papers, and reports devoted to agent-based modelling and simulation as well as works covering the concept of multi-agent systems and their application in various research fields and in the area of PT in particular.
(6) Observe a route of operating PT line in a real-life case study, process data obtained from direct observations revealing actual bus loads and evaluate vehicles’ capacity utilization.

(7) Model and simulate the passenger transportation process along the examined PT line as a multi-agent system (MAS) composed of interacting agents such as bus drivers, buses, private car drivers, cars and passengers. Analyse the behaviour of the modelled system under different simulation scenarios with the purpose of identifying the best combination of vehicle passenger capacity and frequency of service. Summarise the results and outline directions for future research work.

(8) Perform a review of literature sources discussing simulation modelling and its practical application at public transport operations.

(9) Create a simulation framework and develop a simulation model implementing the novel concept of autonomous vehicles in PT providing the flexibility to simulate the passenger transportation process along the route of a PT line, being a part of the whole PTN, as a high-frequency, metro-like PT serviced by driverless vehicles running on isolated (exclusive) lanes.

(10) Apply the developed simulation model along a route serving a PT line through the implementation of different simulation scenarios, performing post-simulation analysis of the simulation output results and drawing reasonable conclusions.

(11) Conduct a review of literature concerning the agent-based modelling approach and multi-agent systems as well as their practical application in solving real-life problems in different research areas, and public transit operations in particular.

(12) Design a multi-agent system composed of agents interacting with each other. Apply a case study of the modelled system in performing fast multi-agent simulation of the passenger transportation process along the routes of newly designed public transport networks characterised with a specific topology and features, discuss the attained results and outline directions for further (follow-up) research work.

1.4 Scope and stages of the research methodology

The connection between the separate components of the thesis is illustrated on a mind map\(^1\) shown in Fig. 1.1 below and the research methodology, which consists of separate stages subdivided into the chapters constituting the thesis, is shown in Figure 1.2.

\(^1\) [https://en.wikipedia.org/wiki/Mind_map](https://en.wikipedia.org/wiki/Mind_map)
Figure 1.1. Connection between the separate components constituting the PhD thesis
Research methodology

Method

Chapter 2: A method of examining the structure and topological properties of public-transport networks

- Utilisation and application of computer programming techniques and algorithms for developing programs and tools that automate the data extraction process, process the data and matrices, doing calculations, find shortest path within a network through the implementation of the Floyd’s algorithm as well as save and export to files the processed data in a format ready for further processing and performing statistical data and network analyses by using other software applications, products and tools;
- Data collection, data entry and data processing, and performing statistical data analyses by using specialised software applications and products enabling to apply regression analyses – least-squares fitting – aimed to reveal and analytically present existing relationships between the studied dependent and independent random variables;
- Performing large-scale network analyses, by using specialized network software, to examine networks for “small-world” properties and scale-free characteristics and evaluating network topological properties (such as average network shortest path length, average network clustering coefficient, average network global and local efficiency) to measure network efficiency which reveals network’s vulnerability and connectedness between PT stops. Utilisation of the evaluated networks’ topological features in calculating of key PT performance measures and indicators.

Chapter 3: Structure and topological properties of public-transport networks using network-science concepts: a case study

Modeling and Simulation

Chapter 4: Modeling the interaction between buses, passengers and cars on a bus route using a multi-agent system

- Processing data regarding the actual PT demand collected from counts (in buses) and evaluating vehicle capacity utilisation;
- An application of the Multi-agent system approach in modeling and simulation of the PT operations along a bus route on a real-life case study under different scenarios, and performing analysis of the simulation output results;
- Data entry, data processing and data analyses – an application of a linear regression (least-squares fitting) in simulation model calibration (observed versus predicted).

Chapter 5: Modeling and simulation of high-frequency autonomous public-transport service

- Processing data regarding the actual PT demand collected from PT counts (in buses) and evaluating vehicle capacity utilisation;
- An application of the Multi-agent system approach in modeling and simulation, by using traffic simulation software, the PT operations along a bus route, on a real-life case study, under different scenarios, and performing analysis of the simulation output results;
- Data entry, data processing and data analyses – an application of a linear regression (least-squares fitting) in simulation model calibration (observed versus predicted).

Chapter 6: Multi-agent simulation of the passenger transportation process in a monorail public transport network with operating autonomous trains: a case study.

- Generating a network with specific topology and features that serves as a fundamental of the subsequently designed monorail route network;
- Adapting the structure of the generated network into Auckland’s urban plan in compliance with the existing road conditions and environmental restrictions, such as roads, streets, residential and business buildings, and others;
- Designing a monorail public transport route network with routes going through the generated network exhibiting small-world features and serviced by autonomous trains;
- Performing a multi-agent simulation of the passenger transportation process along the routes of the designed monorail PTN within the modelled MAS consisting of interacting agents with the purpose of achieving a reliable and punctual public transport service;
- Conducting a post-simulation analysis, discussing the simulation output results, drawing conclusions and outlining directions for future research work.

Figure 1.2. Stages of the research methodology
1.5 Significance of the research

The significance of the doctoral research project can be outlined in the following directions:

(i) The doctoral project, through a novel method combining computer programming techniques, large-scale network and data analyses, bridges network science and public transport operations planning. The application of the method allows examination the structure of public transport networks (bus, metro/subway), and evaluation and analysis of their topological properties, which makes it possible to reveal network types, which in turn would facilitate public transport planners in making network design decisions. The method, through the developed software program which automates and speeds up the process of extraction and processing of GTFS data, could be used to identify possible changes in network type caused by structural changes such as newly created PT routes put in operation or modifications in existing ones. Furthermore, utilising real-life case studies, this thesis presents the application of the method, comprising and implementing network science concepts, in examining vulnerability and fault tolerance of complex PT networks characterised with different topologies. Through performing network reconstruction analysis, the thesis discloses the impact of redesigning PT routes on global and local network efficiency and reveals connectivity weaknesses in the examined networks, which could serve as a starting point in improving the connectivity between the stations/stops within the studied networks.

(ii) On the other hand, this research work opens the door to an application of the novel concept of autonomous vehicles. This concept was applied to the PT field through a simulated autonomous bus service. The work in this direction resulted in a flexible simulation model using the concept of autonomous vehicles. The application of the simulation model, through an implementation of metro-like, high-frequency (short headways), punctual autonomous buses running on isolated lanes (no intersections, no traffic lights, and no congestion) and arriving at bus stops on time, led to the desired outcome: achieving a reliable PT service and reduced passenger waiting times at PT stations. Based on the simulation output parameters, (a) reduced average waiting times (the most significant measure of transit service reliability) and (b) identifying the unserved demand (expressed in terms of the number of passengers who were not transported to their destination point by the end of the simulation), the application of the proposed simulation model, examined under different scenarios, gave an answer to the question: “Which operational strategy has the potential to improve the reliability of PT service?” Another advantage of the applied concept of autonomous vehicles is that it would exclude the need for more bus drivers, which would save operator costs for wages, especially in a case of a high frequency PT service.

(iii) The created multi-agent system, consisting of interacting agents and incorporating a newly-designed monorail public transport network with operating monorail trains (Timan, 2015) that utilise the concept of autonomous (driverless) vehicles, provides the possibility to simulate the
passengers’ transportation process and identify and offer a reliable, punctual and more attractive PT service to current users as well as to prospective ones who use alternative modes of transport such as private cars. In order to realize the above idea, the efforts and the focus in this research refer to developing a MAS composed of three types of agents, PT users (passengers), driverless monorail trains (Kato, Yamazaki, Amazawa, & Tamotsu, 2004), and network segments (route links), all playing specific roles and interacting with one another. Preliminary work by Hadas and Ceder (2008) illustrates the potential existing from the application of multi-agent modelling, with the benefits of handling the algorithms with extensibility, fault tolerances, adaptability, efficiency, distributed problem solving and stability. The developed multi-agent system in this thesis could serve as a starting point for future research work in a direction extending the capabilities of the modelled system, improving the proposed monorail public transport network and performing multi-agent simulations of the passenger transportation process using actual public transport demand data, such as origin-destination matrices, which could be collected through conducting surveys and using questionnaires, performing observations and counts, or directly using census data or data from alternative sources like published reports, articles, papers, etc.

1.6 Intended research contributions of the thesis

The research contributions that the thesis intends to bring to the Transport Engineering field can be summarised as follows:

(i) Creating a novel method which overcomes the limitations of the existing approaches and tools and enables examining of the structure of complex public transport networks and quantitatively evaluating and analysing network topological properties, thus serving as a tool allowing estimation of networks’ efficiency, identifying weaknesses in their structure and outlining directions for network redesign improvements.

(ii) Findings and statistical relationships and dependencies obtained from the practical application of the proposed method on real-life case studies in exploring the structure of existing public transport networks, and evaluation and analysis of their topological features, which would help in identifying network types, performing network reconstruction analysis, and estimating network efficiency.

(iii) Modelling and simulation of the passenger transportation process along an operating PT route into a real-life PTN as a multi-agent system with interacting agents – PT users, buses, bus drivers, private cars, car drivers – aimed to identify the impact of vehicle passenger capacity and the frequency of service on passengers waiting times at the stops of PT.

(iv) Development and application of a simulation model, implementing the novel concept of autonomous cars (driverless vehicles running on isolated/exclusive/priority lanes), which enables
achieving a reliable and punctual, metro-like PT service through examining the effect of an increased frequency of service on passenger waiting times, which in turn impacts the total passenger travel time, on the one hand – and on the other hand, establishes to what extent the increased vehicle frequency contributes to better utilisation of the unused vehicle passenger capacity.

(v) Designing a new public transport network with a specific topology and simulation of the passenger transportation process along the routes of the proposed network into a multi-agent system consisting of the interacting agents, “PT users”, “autonomous vehicles” and “network sections”, with the purpose of achieving a reliable, punctual, fast and convenient PT service.

1.7 Thesis structure

The content of the thesis, shown in Fig. 1.3, is structured in seven chapters – introductory and concluding chapters, five conceptual and methodological chapters (four paper-based and one case study) discussing the research approach applied in achieving the objective of the doctoral project, as follows:

Chapter 1 clearly states the research problem, defines the objective of the thesis and formulates the tasks that need to be solved to achieve the objective. This chapter also highlights the scope and stages of the research methodology by chapters as well as outlining the significance of the research, the intended contributions of the research work and the overall thesis structure.

Chapter 2 introduces a novel method allowing examination of the structure of complex PT networks, evaluation of their topological properties, and analysis the topology of the studied networks. This chapter provides a detailed description of the proposed method and represents a practical application of the method in solving a real-life example with the PTN of Auckland (New Zealand) as a case study. The data collection, extraction and processing accomplished, as well as the performed statistical data and network analyses are clearly explained in each of the steps of the method. The results obtained regarding the network’s topology and type, some concluding remarks, as well as further research directions are discussed at the end of the chapter.

Chapter 3 presents an application of an extended version of the proposed method, utilising network science concepts and tools, to examine and analyse real-world case studies of the structure of two metro PT networks – in Washington DC (United States) and Oslo (Norway). In addition, the case study presents partial network re-design analyses and reveals the impact of the networks’ changes on their topological properties, and vulnerability to unexpected breakdowns directly affecting network connectivity. This chapter ends with a discussion of the results, and a summary of the main findings accompanied by reasonable conclusions and outlined remarks for further research work.
Chapter 4 focuses on a practical application of the multi-agent system approach, in a case study in Auckland (New Zealand), in modelling and simulating the interaction of the agents – PT users, buses, bus drivers, private cars and car drivers – along the route of an operating PT line. This chapter visualises, analyses and discusses the data collected by means of traffic counts and direct observations in buses, which helped to evaluate PT key performance measures that were subsequently used as input parameters in developed scenarios simulating the PT operations into the MAS. This chapter also describes the applied MAS methodology, the utilisation of transport demand modelling and traffic simulation software to model the road network and simulate the interaction between the agents into the examined system. Chapter 4 finishes with discussing the simulation output results, making concluding remarks, giving recommendations, and outlining possible directions for research.

Chapter 5 is devoted to an application of the innovative concept of autonomous cars in modelling and simulation of a high-frequency autonomous PT service using self-driving buses. This chapter provides a clear description of all the steps – starting with outlining the simulation modelling framework, going through the choice of a simulation modelling tool, developing, testing, application and validation of the simulation model on a numerical example to simulate the passenger transportation process along the route of the modelled system – a PT line. The chapter continues with post-simulation analyses of the simulation results for all implemented scenarios. Finally, the chapter summarises the results in reasonable conclusions, and outlines directions for further improvement of the model.

Chapter 6 demonstrates the advantages of the agent-based modelling approach and the opportunities multi-agent simulation platforms provide in modelling and simulation of public-transit operations from a multi-agent system’s perspective which represents the interaction between the agents: passengers, driverless vehicles and route sections within the proposed PTN. The results obtained from the simulations of the passenger transportation process along the routes of the proposed PT network having specific topology and features into the modelled MAS reveal the potential of a possible implementation of a monorail public transport network with autonomous operating vehicles in achieving a reliable, punctual and fast PT service satisfying the existing and future transport demand. The concluding part of this chapter summarises the results and emphasises what could be done to improve the modelled system, which opens the door for follow-up research work.

Chapter 7 summarises the findings and conclusions from the previous chapters of the thesis, represents the merits and the contributions of the doctoral research project, and outlines directions for research work in the future.
Chapter 1

Introduction:
- Research problem;
- Objective of the PhD thesis;
- Tasks of the doctoral research project;
- Scope and stages of the research methodology;
- Significance of the research;
- Intended research contributions of the thesis;

Scope and stages of the research methodology:
- A method of examining the structure and topological properties of public-transport networks;
- Structure and topological properties of public-transport networks using network-science concepts: a case study;
- Modeling the interaction between buses, passengers and cars on a bus route using a multi-agent system;
- Modeling and simulation of high-frequency autonomous public-transport service;
- Multi-agent simulation of the passenger transportation process in a monorail public transport network with operating autonomous trains: a case study.

Chapter 7

Conclusion:
- Summary of the main findings, results and conclusions of the thesis;
- Thesis's contributions;
- Directions for future research work.

Figure 1.3. Structure of the doctoral thesis
CHAPTER 2. A METHOD OF EXAMINING THE STRUCTURE AND TOPOLOGICAL PROPERTIES OF PUBLIC-TRANSPORT NETWORKS

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The lack of a well-defined and systematic approach that overcomes limitations and shortcomings of the existing approaches in exploring the structure and the features of complex public-transport networks and that deals with the emerging difficulties and constraints concerning data availability necessitated the creation of a method which enables to examine these networks and quantitatively evaluate and analyse their topological properties. Such a method could be useful in estimating networks’ efficiency, identifying structural weaknesses as well as working out measures for subsequent redesign of networks and potential improvements on a structural level.

Recent findings in network science (Lewis, 2009; Barabási, 2013) have provided researchers with new tools by which to examine, understand and analyze complex network topologies, thus enabling transport planners to discover features characterizing the structure of PTNs - a serious prerequisite towards successfully improving the structure of existing or the design of new PTNs (Ceder, 2007).

2.1 Objectives

The main objective of the study was to develop a novel and efficient method, coupled with a software tool, of allowing automated extraction and processing of data, and hence of examining and analyzing the structure and topological properties of PTNs. In that way the method serves as a bridge between the theory of complex networks and their practical application, for exploring and analyzing real world complex PNTs. The method itself comprises tools and knowledge of computer programming, large-scale network and statistical data analysis. The proposed method was applied to a real-life PTN in Auckland, New Zealand.

2.2 Literature review: Examination of complex networks

The past few decades have seen a great interest in empirical studies focusing on the network structure and topological properties of Public Transport, whether by road, rail, sea or air (Lin & Ban, 2013). Complex real-life systems like PTNs have continuously been an object of in-depth studies, marked by a large number of works related to Graph Theory and Network Science. These emerged as a result of the notable work, among others, of Erdős and Rényi (1959, 1960) - on the theory and practice of Random Graphs, and subsequently continued with the contributions of Watts and Strogatz (1998) - on “Small-World” Networks (SWN), Newman (2000) on the “small-world”

In their study, Watts and Strogatz (1998) found that in terms of structural properties, networks were highly clustered, similar to the regular lattice, and had small average path lengths (APL) specific to random networks (RN). They named these networks “small-world”, as is shown in Figure 2.1, by analogy with the so-called “small-world” phenomenon (Milgram, 1967), also known as six degrees of separation (Guare, 1990). Watts and Strogatz’s work effectively initiated the myriad studies focusing on examining real-life networks for “small-world” properties.

Thus, for example, as a result of their study of the topology (Lewis, 2009; Rodrigue, Comtois & Slack, 2013) of large and diverse networks, Barabási and Albert (1999) concluded that “independent of the system and the identity of its constituents, the probability $P(k)$ that a vertex in the network interacts with $k$ other vertices decays as a power-law, following $P(k) \sim k^{-\gamma}$,” where the exponent $\gamma$ is called a scaling factor.

Barabási and Albert (1999) proved that the existing network models, such as Erdős and Rényi (ER) and Watts and Strogatz (WS), failed in two important features of real-life networks: growth and preferential attachment. In random networks (ER), for example, the number of nodes $N$ is fixed, and each two vertices are connected with a given probability $p$; the values of this probability, with which any vertex has $k$ edges, are distributed according to a Poisson distribution. On the other hand, according to the WS model, “small-world” networks have $N$ vertices forming a one-dimensional lattice, in which each node is connected to two other vertices – the nearest one and the next nearest – with a probability $p$, whose value is selected randomly. The important feature in the ER and WS models is that the probability $p$ of a randomly selected vertex being highly connected and having a large value for $k$ decreases following an exponential distribution, which means that highly connected vertices in these networks are in practice absent. In contrast, the finding according to which the probability $P(k)$ of a given vertex having $k$ neighbors follows a power-law distribution;

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**Figure 2.1. Random rewiring procedure of the Watts-Strogatz model (Watts & Strogatz, 1998)**
within these networks, therefore, it is more likely that highly connected vertices will occur. These
are called scale-free networks and shown in Figure 2.2.

Figure 2.2. Complex networks (l-r.): (a) “Small-World”, (b) Scale-Free and (c) Random. Adapted from (Huang, Sun & Lin, 2005)

In order to prove that power-law scaling requires both features – growth and preferential attachment – simultaneously, Barabási and Albert (1999) built two types of models: (i) Albert’s growth model (A), which keeps the property’s growth and the attachment to which is not preferential but uniform (i.e., each new vertex connects to the existing vertices with equal probability) and (ii) Barabási’s preferential attachment model (B), in which the number of vertices is fixed (i.e., there is no growth, and the attachment is made preferentially - it is more likely that a new vertex connects to highly connected vertex, leading to the occurrence of the “rich-get-richer” phenomenon). Combining B and A models in the well-known Barabási-Albert (BA) model (Albert & Barabási, 2002), characterized by growth and preferential attachment, has led to the generation of a network having a power-law node degree distribution. Both the growth and the preferential attachment models are specifically design mechanisms for networks, such as PTNs, and scale-free networks.

Newman (2000) continues the discussion of the “small-world” effect. Based on an exhaustive review of the significant research related to “small-world” phenomenon and on the analyses he has performed, Newman summarizes that “the most important result is that small-world graphs show behaviors very different from either regular lattices or random graphs.” One of these behaviours that may be of interest is that in addition to the “small-world” effect, there are real-life networks that exhibit and other features important to their functioning. A real example is the WWW, whose node-degree distribution (NDD) seems to be a power-law (Barabási & Albert, 1999; Adamic & Huberman, 2000).

In addition to “small-world” networks, Albert and Barabási (2002) further extended the discussion to include recent findings regarding complex networks, paying special attention to the topic of network topology and dynamic properties from a statistical mechanics point of view.
In order to consider “small-world” networks and their behaviour in both their local and global aspects, instead of the two clustering coefficient (CC) and average path length measures used by Watts and Strogatz (1998), Latora and Marchiori (2001) introduced the term “efficiency” as a measure showing the extent to which information can be exchanged within a given network. Thus, they provide a better physical explanation of the “small-world” phenomenon, allowing more precise quantitative analyses to be performed not only of unweighted but also of weighted graphs. Analysing various large real networks, Latora and Marchiori find that the main underlying principle characterizing the structure of all the networks examined is the “small-world” principle.

Barabási and Bonabeau (2003) summarized the major findings about scale-free and “small-world” networks obtained in recent years as a result of studies of real complex networks. They compared and outlined the main differences between two types of networks: (i) Random graphs whose structure resemble a highway system, as is shown in Figure 2.3, in which most of the nodes are connected randomly to other nodes having almost the same node degree (thereby excluding the possibility of the appearance of hubs) and are distributed following a Poisson distribution. Since the probability P(k) that a given vertex has k edges decreases exponentially for nodes with high values of k, random networks are also known as exponential networks. (ii) Scale-free networks resembling in structure an airline system, which can be considered hub-based, characterized by a power-law degree distribution. Most of the vertices in scale-free networks have a small number of links, but there are also a small number of nodes, called hubs, that have multiple connections.

![Bell Curve](image1.png)  ![Power-Law Distribution](image2.png)

*Figure 2.3. An example of highway (a) and airline (b) transportation systems (Barabási, 2002)*
The new knowledge about SFNs and SWNs have given rise to numerous studies in various fields of science, transport among them, that mainly examine and analyze network topology through an evaluation of network characteristics, such as CC, APL, NDD and efficiency.

Wu, Sun, and Huang (2004) report that their work is the first attempt ever made to describe, examine and provide an explanation of the topology of real urban transit networks, applying for that purpose the comparatively new knowledge about SFNs. The results of the data analysis they performed, which explored Beijing’s complex transit network, as composed of origin and destination sites, showed that the system exhibited characteristics specific related to SFNs: (i) approximately 90% of the nodes had a small node degree and only a few nodes (about 10%) were highly connected; (ii) the NDD was a power-law, whose parameter of 2.24 was within the range of values $2 < \gamma < 3$ in SFNs (Barabási & Bonabeau, 2003).

Two years later, Wu, Gao, and Sun (2006) examined Beijing’s entire PTN (4,806 nodes, 625 routes and 17,456 edges), in which nodes represented bus stops and two stops were connected by an edge only if there were a route servicing them. In order to examine whether the PTN exhibits “small-world” properties, they compared it with an RN of the same size (4,806 nodes) and the same average node degree (equal to 3.63). The comparison of the calculated with the theoretical values for CC and APL demonstrates that PTN is a SWN.

Von Ferber, Holovatch, and Palchykov (2005) examined the PTNs of Berlin (198 routes and 2,952 stations), Düsseldorf (124 routes and 1,615 stations) and Paris (232 routes and 4,003 stations). The steps they followed in conducting their study and performing analyses of PTNs were these: (i) selection of the PTN to be observed, (ii) creating an ordered list of stations serviced by the routes of each PT line, using data extracted from the timetable and (iii) performing analyses and examining the statistics obtained about the number of PT lines servicing a given station (i.e., information about NDD and the probability $P(k)$ that a given station would be serviced by $k$ routes). The analyses show that the distribution of the stations is a power-law with a scaling factor, obtained through least squares fitting, of $\gamma = 2.45$ for Düsseldorf, $\gamma = 2.9$ for Berlin and $\gamma = 2.94$ for Paris; all being $2 < \gamma < 3$ (Barabási & Bonabeau, 2003) show that these PTNs exhibit characteristics of SFNs.

Fundamental work in the direction of performing statistical analysis of PTNs and examining network topology was conducted by Sienkiewicz and Holyst (2005). Their comparative study reported results obtained for the PT systems of 22 cities in Poland, each containing from 152 to 2,881 bus stops. One of the main findings is that although the PT systems of these cities differ in size, they share the same network topological features, “such as degree and path length distributions, logarithmic dependence of distances on node-degrees, or a power-law decay of clustering coefficient for large node degrees.” In order to examine and analyze these features,
Sienkiewicz and Holyst used the idea of space L, illustrated in Figure 2.4, in which the node degree was “the number of directions one can take from a given node,” the space of stops showing a station’s importance (from an operator’s perspective); and space P, the network topology, in which the node degree was “the number of nodes reachable using a single route,” the space of exchanges thus showing the number of transfers (from the user’s perspective).

The results of the analysis for the applied network topologies show that the empirical degree distribution for Space L follows a power-law function \( P(k) \sim k^{-\gamma} \), with exponent \( \gamma = 2.4-4.1 \) (\( \gamma > 3 \) in 15 of the 22 cities, differing in this way from Barabási-Albert’s scale-free network model (Barabási & Albert, 1999), whereas the distribution in Space P is fitted by exponential function \( P(k) \sim e^{-\alpha k} \), with parameter \( \alpha = 0.013-0.050 \). “Small-world” behavior has been observed for both network topologies – highly clustered networks with small APL.

Xu, Hu, Liu F., and Liu L. (2007), representing networks through L-space and P-space topologies, examined network properties, such as average CC, APL and NDD, characterizing the public bus transport networks of three large cities in China. The results show that NDDs in L-space are power-law, described by function \( P(k) \sim k^{-\gamma} \), with the value of the scaling exponent \( \gamma \) between 2.5 and 3.0; whereas for the P-space network topology, the cumulative distribution is described by the function \( P(k) = Ae^{-\alpha k} \), with values of \( \alpha \) as follows: \( \alpha = 0.0075\pm0.0018 \) for Beijing, \( \alpha=0.0136\pm0.0009 \) for Shanghai and \( \alpha = 0.0182\pm0.0008 \) for Nanjing.

Chen, Li, and He (2007) carried out a study that examined and statistically analyzed the properties of the urban bus transportation networks of four large Chinese cities; their efforts focused on a bus transportation network (BTN), as buses are the dominating PT mode in China. The BTN was represented by nodes (stops) and edges serving as links between each two stops in case these stops were serviced by this route. They used P-space topology, as the network can be projected as a bipartite graph (Seaton & Hackett, 2004). The results of this survey show that the degree distributions of the networks studied are exponential and can be approximated by a function of type \( P(k) \sim e^{-\nu k} \). Chen, Li and He (2007) also introduced another useful statistical parameter, “the
number of bus routes a stop joins”; $R$, representing the number of routes by which this stop is serviced. They demonstrate that the distribution of bus routes that a stop joins is also exponential and can be described as $P(R) \sim e^{BR}$, thus proving that the empirical degree distributions and the distributions of the bus routes that a given stop joins are exponential for all the cities. The main finding here is that the organization of the BTNs examined is random, without the dominance of a small number of highly connected nodes like hubs.

Lu and Shi (2007) focused on the definition, description and examination of the complexity of the PTNs of three large Chinese cities. They represented the networks studied by three topologies depicted in Figure 2.5: public transportation route network (PTRN), public transportation transfer network (PTTN) and bus station network (BSN). The results showed, on the one hand, the practical importance of network parameters – in BTN, for example, the node degree corresponds to the number of routes serving this stop. On the other hand, the results demonstrate that PTNs exhibit some of the features specific to complex networks – PTTN shows a “small-world” effect with power-law or exponential NDD; and BSN exhibits “small-world” properties with a distribution between exponential and power-law. In contrast, the results for PTRN regarding CC and APL are commensurate with the theoretical values of these parameters in random graphs.

Figure 2.5. PT Networks (Lu & Shi, 2007)

Similar to Sienkiewicz and Holyst (2005), Chen, Li, and He (2007) and Lu and Shi (2007), Von Ferber, T. Holovatch, L. Holovatch, and Palchykov (2009) examined the topological properties of PTNs of 14 then-unexplored large cities around the world, using various network representations, such as L, B, P and C-space topologies, illustrated in Figure 2.6. Their results showed that for most of these networks, which were represented in an L-space topology and showed a power-law NDD, the scaling exponent $\gamma$ had a value of $\gamma_L \sim 4$, which was close to the values for some PTNs in the case study of Poland (Sienkiewicz & Holyst, 2005): $\gamma_L = 3.77$ for Kraków (940 stations), $\gamma_L = 3.9$ for Łódź (1,023 stops) and $\gamma_L = 3.44$ for Warsaw (1,530 vertices). The main finding is that all the PTNs examined appear to exhibit “small-world” properties; i.e., large CC and relatively small APL.
In comparison with some studies that considered PTNs as static systems, Yan and Wang (2009) sought to perform an empirical analysis and examine topological properties of the PTNs. They employed statistical data covering a twelve-year period, which allowed them to study, reproduce and explain the evolutionary mechanism and functioning of the system observed, for which they applied a simulation model based on accelerating growth and non-linear preference attachment. Their results show that the PTN examined was a “small-world” network with an accelerated growth with respect to time and with evolution characterized not only by random, but also by preferential attachment.

As a result of the exhaustive review that Derrible and Kennedy (2011) conducted of notable contributions to graph theory and network science – in the areas of transit-network design and network topological indicators (Vuchic, 2005); SWNs (Watts & Strogatz, 1998; Latora & Marchiori, 2001; Latora & Marchiori, 2002); and SFNs (Barabási & Albert, 1999), including Transit Network Characteristics (Derrible & Kennedy, 2010) of metro networks – they concluded that there were three challenges that had to be solved in the near future: (i) a standard methodology for examining transit systems; (ii) the presence of more than one mode of PT to be taken into consideration (i.e., the methodology has to deal with the modal integration); and (iii) preparation of a comprehensive list of network-design indicators useful to transport planners in designing PT networks.

Recently Zhang, Peng, Zhang, and Xue (2012) discussed the possibilities of how, by using the three types of network representation (topologies), such as a bus station network (Space L), a bus transfer network (Space P) and a bus line network, urban bus-transport networks composed of two components – stations and lines – could be modelled as a complex network. They assert that a given model can be examined in four steps by taking advantage of graph theory: (i) defining a node, (ii) generating an edge, (iii) generating an adjacency matrix (De Nooy, Mrvar, & Batagelj, 2005), and (iv) computing topological properties and performing network simulation. The simulation results reveal that for the proposed bus-line model, a simulation using the values of CC and APL show that this network exhibit “small-world” features; i.e., high clustering coefficient and short APL. Unlike other previously examined networks, here the NDD is not power-law, but random.
In a more recent study of the topology properties of Beijing’s bus network, Yao (2013) applied the two widely used network representation approaches – Space L (to examine NDD, CC and APL) and Space P (to assess the average transfer time). The results of the analyses showed that in the L-space representation, Beijing’s network was an SFN with a shifted power-law NDD in which 99% of the bus stations had a node degree of less than 10 and only 4.48% had a degree equal to 1. On the other hand, the distribution of the proportion of bus stations according to the number of lines they service in space P is exponential, \( f(x) = 0.79e^{-0.67x} \).

Curtis and Scheurer (2010) propose a planning tool enabling to perform spatial network analysis for multi-modal urban transport systems. The authors assessed accessibility of the transport systems by using spatial separation measures, contour measures, gravity measures, time-space measures, utility measures, and network measures. Their main conclusion drawn is that there is no ideal single measure for accessibility, and thus a combination of measures is recommended for use. For the examination of network properties, the authors use measures, such as node degree, average node degree, node degree distribution, average (shortest) path length and global efficiency; the measure of global efficiency is expressed by the inverse average shortest path length between any pairs of nodes within the network.

Hadas (2013) and Mishra, Welch, and Jha (2012) propose methodologies for measuring and assessing the connectivity of public-transport systems using an indication of the level of coordination between PT routes, coverage, timetables, and operational capacity and speed. Hadas (2013) proposes a unified methodology, mainly based on Google Transit data, to conduct spatial analysis using GIS techniques and tools. The methodology is implemented using the following five connectivity indicators developed: (a) transportation network coverage level; (b) average speed; (c) intersection coverage level; (d) stop transfer potential; and (e) route overlap. Mishra, Welch, and Jha (2012) propose performance indicators for node, link, transfer center and region; these indicators assess public-transport connectivity using a graph-theory approach.

In addition, Hadas and Ranjitkar (2012) model PT connectivity using measures of ‘value of time’ and ‘quality of transfer’. They use data taken from GTFS (PTNs attributes), transport agencies (PT demand and forecasts) and GIS (data on existing road network).
2.3 Method

The main objective of the method developed was to provide a framework enabling the relatively easy examination and efficient analysis of the topological structure and properties of the PTNs studied. The proposed method consists of the following nine steps shown in Figure 2.7.

![Figure 2.7. Flow-chart representing the sequence of steps outlining the logic of the proposed method](image)

According to the proposed method, the process of examining PTNs follows the logic presented below:

**STEP 1:** Transit agencies and transit operators provide GTFS data\(^2\), filling in templates (‘*.txt’ files) in a GTFS format\(^3\). These text files are then published online in the form of GTFS “feeds” containing publicly-accessible for downloading data regarding the PT route lines and timetables.

**STEP 2:** As input data for the proposed method, the transit-schedule data published on the Internet by transit agencies and transport operators according to the GTFS file format will be used. This takes the form of text files, such as “stops.txt,” “routes.txt,” “trips.txt,” “stop_times.txt” and others that contain timetable information for the PT operating modes (tram, subway, rail, bus, etc.), such as number of routes running along the separate PT lines, the stops (given by their IDs, codes, coordinates and names) that are serviced by these routes, as well as other useful data for a given period of time.

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\(^2\) [https://developers.google.com/transit/gtfs/](https://developers.google.com/transit/gtfs/)
\(^3\) [https://code.google.com/p/googletransitdatafeed/wiki/PublicFeeds](https://code.google.com/p/googletransitdatafeed/wiki/PublicFeeds)
\(^4\) [https://developers.google.com/transit/gtfs/reference](https://developers.google.com/transit/gtfs/reference)
The terms ‘line’ and ‘route’ are used in this work with different meanings, though often these terms coincide. Similarly to the definition of a transit line given by Vuchic (2005), the term ‘line’ is an accompanying number, e.g., Line 123, appearing in the PT timetable, stops and elsewhere. The term ‘route’ is the sequence of stops (or stations) along a PT line. In practice, depending on the existing fluctuated passenger demand and other factors (such as one-way and two-way road sections), a PT line can be served by more than one route. For instance, Figure 2.8 illustrates a single PT line served by two routes, Route 1, part (a) of Figure 2.8, is for, say, peak hours and Route 2 for off-peak hours. In addition, it may so happen that some trips cover all the stops and others are only part of the stops meaning, in this work’s terms, different routes of the same line.

![Diagram](image)

(a) Route 1 along PT line 123  (b) Route 2 along PT line 123

Figure 2.8. Example of PT line served by two different routes

STEP 3: Software program - The required information and data provided by transit agencies and operators (STEP 1) as GTFS data (text files organized as tables with the respective columns, STEP2) serve as input for a software program developed (using Java\(^5\) within Eclipse\(^6\)) for the purpose of extracting, reading, properly processing and exporting the processed data for further analyses. As a result, the routes reproduced as a sequence of stops for the selected operating modes will be exported for further processing and analysis in two directions: on the one hand, to examine whether the PTN studied displays scale-free characteristics (STEP 4); on the other hand, to explore whether the PTN exhibits “small-world” properties (STEP 7).

STEP 4: Export of the processed data to Microsoft® Excel (Microsoft Corporation, 2010) to explore the scale-free characteristics of PTN. In order to examine whether the PT network exhibits scale-free properties, the processed on STEP 3 data on stops and the number of lines servicing each stop is exported to Excel for regression analysis. In case further regression is needed, comprising features beyond the scope and capabilities of Excel, such as non-linear fitting with functions different from those Excel offers, the data processed in the Excel working environment is sent to SPSS (IBM Corporation, 2012) to take advantage of its strengths (STEP 5).

STEP 5: SPSS provides the possibility of carrying out additional regression analyses, such as curve estimation and non-linear fitting. Within the SPSS environment, the data is processed and analyzed for the purpose of revealing existing relationships between the dependent and independent variables.

\(^6\) https://www.eclipse.org
STEP 6: This step includes visualization of the output results obtained from the statistical data analysis; their interpretation, on the basis of which a decision will be made whether or not the PTN is a scale-free or another type of network and conclusions drawn about the mechanism of network formation; these can serve as a basis for PT planners when making decisions justifying the redesign of existing or the design of new PTNs.

STEP 7: Exploring the PTN for “small-world” properties. The data on stops, on the one hand, and on the routes represented as a sequence of the stops they service, on the other hand, is used by the software program developed to reproduce the network’s structure and to export it in a ‘*.dat’ file compatible with the Pajek program enabling network visualization and large-scale network analysis (De Nooy, Mrvar, & Batagelj, 2005; Mrvar & Batagelj, 2013; Batagelj, Mrvar, & Zaveršnik, 2014). The PTN structure is represented in the form of an adjacency matrix between the stops, with \( a_{ij} \) representing the connectivity between the stops within the PTN and the matrix elements \( a_{ij} \) having the values \( a_{ij} = 1 \) if two stops are connected (i.e., they are consecutive stops along at least one route servicing them) and \( a_{ij} = 0 \) otherwise. The completed adjacency matrix written in a ‘*.dat’ file will serve as input to Pajek to visualise and analyse complex networks. Because of specific features and the complexity with which they are characterized, PTNs are represented as directed, unweighted graphs; i.e., there will be arcs with weights equal to 1 linking only those pairs of stops that are consecutive stops along one or more routes.

STEP 8: Interaction between the two programs – the developed software program and Pajek – is implemented through the adjacency matrix created, whose aim is to perform transfer and subsequent transformations of data so as to use Pajek to visualize, explore and analyse the public-transport network for “small-world” effects in terms of the calculated values of the network’s topological properties CC and APL.

STEP 9: This step of the methodology represents the output results in regard to the calculated values of CC and APL, which will serve to make decisions about the structure of the PTN. In this step, the calculated empirical values of these parameters will be compared with the theoretical values of random graphs, based on which a decision will be made about the network’s topological structure – whether it exhibits “small-world” properties; that is, larger values of CC and smaller APL values compared to random networks.

STEP 10: The last step of the method involves equations enabling to evaluate PT performance measures and indicators. This step is based on the examined network’s topological properties, such as APL, computed as a result of the analyses performed in STEP 9; it serves as a “bridge” between network science theory and PT operations planning. In other words, this step connects between the in-depth literature review of network science, graph theory and the PT domain.
In this step the APL is defined as $AS_P$ which is the number of sections/stops along the average shortest path across all shortest origin-destination (O-D) paths $P$ in the network. The average number of sections/stops per individual route, $AS_R$, estimated by the computer program and $AS_P$, can be used to calculate the average number of routes, $AR_{OD}$, available in the network for an O-D pair along the shortest O-D path; that is,

$$AR_{OD} = \frac{AS_P}{AS_R}. \quad (2.1)$$

The term ‘shortest path’ means the least number of consecutive sections (with length of 1) or intermediate stops between the terminal stations, i.e., between the origin and destination points. $AS_P$ is:

$$AS_P = \frac{\sum_{p=1}^{P} S_P}{P}, \quad (2.2)$$

Where $S_P$ is the length of shortest path $p$ (for $p = 1, \ldots, P$) expressed by the number of sections/stops between the terminal stations; note that ‘section’ is the path’s segment between two adjacent stops. $AS_R$ is:

$$AS_R = \frac{\sum_{r=1}^{R} S_r}{R}, \quad (2.3)$$

where $S_r$ is the number of sections/stops for route $r$ (for $r = 1, \ldots, R$) and $R$ is the number of routes within the network.

The value of $AR_{OD}$ shows the average number of routes between two O-D stops. Its value does not provide any information on how many transfers passengers would need to make. Therefore, in order to calculate the PT demand that cannot be satisfied by direct routes and to estimate the share this demand takes out of the total O-D demand we need the O-D matrix.

Because $AR_{OD}$ does not consider the PT demand and its variability, new performance measure, $AR_{OD_d}$, is introduced. It expresses the average number of routes required to cover the O-D demand $d$ as follows:

$$AR_{OD_d} = \frac{AS_{P_d}}{AS_R}, \quad (2.4)$$

where $AS_{P_d}$ is computed in Equation (2.5) as a weighted average sum of the O-D demand $d_{i,j}$ and the shortest O-D paths $S_{P_{i,j}}$ between the pairs of nodes $i$ and $j$ measured in terms of the number of sections, and $n$ is the number of vertices (stops) in the network; that is,
\[ AS_{p_d} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} S_{p_{i,j}}d_{i,j}}{\sum_{i=1}^{n} \sum_{j=1}^{n} d_{i,j}}, \] (2.5)

The following numerical example further illustrates the meaning of the PT performance measures and definitions developed. Given is a PT route network composed of twelve stops shown in Figure 2.9(a) and served by three (bus) lines – two long lines and one short line sharing a common terminal station (Node 3), as follows:

- bus lines 1 served by Route 1 going through stops 1-2-3
- bus line 2 served by Route 2 going through stops 3-4-5-6-7-8
- bus line 3 served by Route 3 going through stops 3-9-10-11-12

For the sake of clarity, the PT route network of the example is illustrated in an L-space topology in Figure 2.9(b). The adjacency matrix appears in Appendix A, Table A.1. In addition, Table A.2 shows the shortest O-D paths measured by number of sections. For instance, the shortest path from Node 1 to Node 8 has a length of seven sections and goes through nodes 1-2-3-4-5-6-7-8.

Following Lewis (2009) the average shortest path length \( AS_P \) can also be calculated; that is, the sum of the non-zero elements \( S_{p_{i,j}} \) in the matrix of shortest O-D paths \( P \) is divided by the sum of the non-zero elements \( l_{i,j} \) in the accessibility matrix \( L \). The latter matrix represents the accessibility between the nodes within the network through a shortest path. Therefore, for computing \( AS_P \), the following formulae can be used:
\[
AS_p = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} S_{p_{i,j}}}{\sum_{i=1}^{n} \sum_{j=1}^{n} l_{i,j}},
\]

(2.6)

where \( S_{p_{i,j}} \) is the shortest O-D path between nodes \( i \) and \( j \) expressed by the number of sections, and \( l_{i,j} = 1 \) in case node \( j \) is accessible through a path from node \( i \). Otherwise \( l_{i,j} = 0 \).

Equation (2.7) provides the useful transferring coefficient as an indicator for the average number of single trips required to satisfy the O-D demand. This coefficient gives the proportion of the part of the demand not covered by direct routes; that is, the part that must use a transfer.

\[
C_{tr} = \frac{d_t + d_{tr} \cdot N_{tr}}{d_t},
\]

(2.7)

where \( N_{tr} \) is a coefficient reflecting the number of routes required to cover the unsatisfied demand \( d_{tr} \) for any O-D pair. If assuming that the demand \( d_{tr} \) will be covered with no more than one transfer, i.e., using 2 routes from O to D, then \( N_{tr} = 2 \); \( d_t \), \( d_d \), \( d_{tr} \) are, respectively, the total O-D PT passenger demand, the demand covered by direct routes, and the O-D demand requiring transfers. The O-D demand is:

\[
d_t = \sum_{i=1}^{n} \sum_{j=1}^{n} d_{i,j},
\]

(2.8)

where \( d_{i,j} \) - the PT demand between any pair of nodes \( i \) and \( j \), \( \forall \ i \neq j \), in the O-D demand matrix \( D \).

The demand covered by direct routes is:

\[
d_d = d_t - d_{tr},
\]

(2.9)

where \( d_{tr} \) is calculated as a sum of the elements \( d_{tr_{i,j}} \) in the matrix \( U \) of the unsatisfied (via a direct route between the origin and destination stops) PT demand. There may be the following two cases:

- if there exists a direct route between the nodes \( i \) and \( j \), i.e., \( r_{i,j} = 1 \), then \( d_{tr_{i,j}} = 0 \);
- if there is no a direct route between \( i \) and \( j \), then \( d_{tr_{i,j}} = d_{i,j} \).

The indicator \( S_{dtr} \) showing the proportion of O-D demand requiring transfers is:

\[
S_{dtr} = \frac{d_{tr}}{d_t}
\]

(2.10)

Equation (2.10) shows the proportion of the demand requiring transfers divided by the total demand.
There is a need now to explicate how the defined measures, such as $AS_P$, $AS_R$, $AR_{OD}$ and $AR_{OD_d}$, can be applied with the use of the developed indicators in Equations (2.7) to (2.10). For this explication twelve variants of PT route-network configurations were developed and subsequently analysed for the example problem of Figure 2.9; the twelve variants are shown in Table A.7.

The assumptions used for this explication of the example problem on Figure 2.9 are:

- The O-D demand that cannot be covered by direct routes uses only one transfer.
- The street (road) network remains unchanged, thus $AS_P$ is constant; however, the average number of sections per route is variable.
- The number of lines is unchanged (3 lines), but the number of sections along the routes serving these three lines is variable. Therefore, the PT route network is changed only in terms of the length (number of sections) of the separate routes.
- No demand assignment is considered for the O-D demand that cannot be covered by direct routes.
- There is no consideration/determination of vehicle (bus) frequency and the number of vehicles required.

Only the user’s perspective is considered by the twelve variants; certainly, the operator’s perspective should be taken into account too, such as the consideration of operating costs incurred based on vehicle-km performed.

Redesigning existing PT route network enables changing route lengths so as to obtain the desired proportion of O-D PT demand to be covered with trips including transfers. This can be attained by two steps with opposite solution directions: (i) given a desired average route length ($AS_R$), to determine the proportion (and the amount) of the O-D demand requiring trips with transfers, and (ii) given the proportion (and the amount) of the O-D demand requiring making transfers, to determine $AS_R$.

Following the establishment of the measures and indicators, and the formulation of the developed method a further clarification is provided using the example problem on Figure 2.9. We start with Variant 1 of Figure 2.9(a) using Equations (2.1) to (2.10). The performance measures and indicators obtained are displayed in Table A.7, Appendix A. The transfer coefficient determined is $C_{tr} = 1.76$, that is, 76% of the total O-D demand is not covered by direct routes and, hence, it needs the use of transfers. Figure 2.10 depicts the route configuration of Variant 2, that is, extension of Route 1 (1-2-3 and 9). The calculation for Variant 2 results in $C_{tr} = 1.74$, or with 2% more having direct routes, which is because of the increased average number of sections per route $AS_R$ from 3.67 (Variant 1) to 4.00 (Variant 2) and decreased average required number of routes $AR_{OD}$ from 1.02 to 0.93 ($AR_{OD_d}$ is changed from 1.32 to 1.21).
It is interesting to note that for Variant 12 (Table A.7), $S_{dtr} = 0.00$ and thus the transfer coefficient is $C_{tr} = 1.00$, because each pair of nodes is directly accessible through routes. In practice such a result can be implemented at the price of extending the average route length up to $AS_R = 7.33$ sections per route leading to decreased $AR_{OD}$ and $AR_{OD_d}$ to 0.51 and 0.66 routes, respectively.

Appendix A, related to the example problem on Figure 2.9, contains Figures A.1, A.2, and A.3 to show the relationships between the variables of Equations (2.1) to (2.10). These figures depict and show the regression equations describing these relationships.

![Figure 2.10. Configuration of the example PT route-network (variant 2)](image)

Let us introduce another scenario. Given that $S_{dtr} = 0.5$ (50% unsatisfied demand, not covered by direct routes), by using the relationship in Figure A.3 against the value of $S_{dtr}$ on the y-axis, the average required number of routes is $AR_{OD_d} = 0.88$. Then, against that value of $AR_{OD_d}$ in Fig. A.2, we arrive at $AR_{OD} = 0.68$ routes on average. Finally, using Figure A.1, for $AR_{OD} = 0.68$ we obtain $AS_R = 5.5$ sections per route on the average. Therefore, in order to reach the desired proportion of 50% we need to increase the average route length, within the network, up to 5.5 sections compared to Variant 2 with $AS_R = 3.67$ sections. Now the opposite consideration takes place with a given $AS_R = 6.5$ sections per route. On Figure A.1 the corresponding $AR_{OD} = 0.57$ routes, and using Figure A.2 for that value of $AR_{OD}$ we obtain $AR_{OD_d} = 0.75$ which on Figure A.3 corresponds to $S_{dtr} = 0.25$. The latter can be interpreted as follows. The expected reduction of the proportion of the unsatisfied O-D demand not covered by direct routes, from 0.5 to 0.25, can be attained by increasing the average route length from 5.5 to 6.5 sections per route, that is, approximately at the “cost” of an 18.2% length extension.
The above numerical example demonstrates the need for further research in the direction of performing sensitivity analysis concerning all of the variables. That is, to explore the impact of different numbers of routes, route lengths and combinations of network configurations on the average required number of routes, the proportion of the O-D PT demand that can be serviced along direct routes, and of the transfer coefficient.

### 2.4 Case study

In order to demonstrate the potential of the method developed and to show its efficiency, the foregoing step-by-step approach was applied to a real-life situation in Auckland, New Zealand. As a case study the PTN of Auckland was chosen with the goal of exploring it as a complex network.

#### 2.4.1 Data Collection

The inconvenience in accessing and gathering PT data was overcome through the use of available information provided by transport agencies and operators online (STEP 1) in the form of GTFS feeds (STEP 2). The PT route network, composed of nodes (representing 6,101 stops) and arcs (connections established between each pair of stops if they are consecutive stops along a route), is currently serviced by 1,381 routes in total. Three operating modes compose the PT system – buses, with the dominant share of about 95% (1,317 routes) of all routes in Auckland, followed by trains and ferries. Being a dominant mode, bus routes (regular and express) cover 5 areas in Auckland – Central Auckland, North Shore, Eastern, Western and Southern suburbs, shown in Figure 2.11. According to the information provided in the file “Calendar.txt”, the observed period of time for which the PTN was considered – lines, routes, stops and timetables – starts on the date 3rd of May 2014 and ends on the date 6th of June 2014.

The complexity of the Auckland PTN, expressed, on the one hand, by the large number of routes and stops serviced by these routes and, on the other hand, by the fact that there are routes that are not fixed during the day and, in fact, differ in direction, as well as in the number of stops they service, convinced us to construct this PTN as a directed graph (Lin & Ban, 2013). This representation is in contrast to some earlier studies, in which because of simplifications – such as considering the route network in only one direction and presenting it as an undirected graph composed of nodes representing the same stop for both directions – the network represented differs from the actual network. It is important to mention that each stop in Auckland has its own unique code (stop_code in GTFS), which means that each stop is represented in both directions as a different node and that the link connecting two consecutive stops along the same route will be an arc (following the respective direction) instead of an edge. Moreover, as already mentioned, the number of stops may be different in each direction. For that reason, it is not relevant to use one
node representing two stops serviced by vehicles running along the same route, but in the two
directions. This means that the adjacency matrix in our case will not be symmetric. The examined
PT network was represented in an L-space topology, in Figure 2.6b, as “for the L-space graph the
node degree of a station is the number of other stations within one stop distance.” (Von Ferber,
Holovatch T., Holovatch Y., & Palchykov, 2009)

![Figure 2.11. (a) Map of Auckland (Auckland Transport. Central guide, 2014a); (b) Schematic Auckland’s PT network using TransCAD (Caliper Corporation, 2013)](image)

2.4.2 Data processing

In order to efficiently process a significant proportion of the large volume of data that GTFS
feeds contain and to facilitate and speed up the processing of data, a software program (STEP 3)
was developed using the object-oriented programming language Java and taking advantage of its
powerful functionality, flexibility and opportunities it provides for extension. The role of this
program is to extract from GTFS text files the needed data, to process this data and, as a result, to
reproduce the PT routes as a sequence of stops. Finally, the data will be prepared and organized in
the best possible manner for export for further analysis and consideration with other software
applications, products and packages, such as MS Excel and SPSS for data modelling and analysis
and Pajek for network visualization and large-scale network analysis.

Depending on the purposes of this case study, the data on the whole route network (buses, trains
and ferries) or on bus routes only would be exported for use in two main directions: to examine the
scale-free characteristics of the PT network (STEPS 4-6) and to examine “small-world” properties
of the PT network being studied (STEPS 7-9).
2.4.3 Examining PTN for scale-free characteristics

In STEPS 4-6, data was exported to an Excel file about stops (for all operating modes, as well as for bus routes only) and about the number of lines servicing each stop; this number of lines can differ at different points in time during the observed period of time. The number of lines, served by a given stop, represents, to some extent, the importance of this stop. The exported data was analyzed using Excel’s function (STEP 4) of performing non-linear fitting. Thereafter, the data was imported into SPSS (STEP 5) for performing further non-linear regression analyses, such as curve estimation and non-linear regression analysis.

As a result of the two identical analyses performed using (i) data about the whole route network comprising the three modes of transport – buses, trains and ferries – and the stops their routes currently service and (ii) data about the bus lines and the bus stops these routes service at the time of the case study, it was found that there is a non-linear dependence between the stops and the number of lines servicing each stop within the whole PTN (including bus, train and ferry routes), and within the bus PTN in particular.

In order to analytically describe the observed relationship, the following function was used

\[ P = f(k) \] (2.11)

Equation (2.11) expresses the probability \( P \) of a randomly selected node (stop) having \( k \) neighbors or links (connections, through PT lines, to other stops in the network).

It was demonstrated in Table 2.1 and Figure 2.12 that the revealed non-linear relationship between \( P \) and \( k \) is best fitted with two types of functions:

- power-law (Newman, 2005; Adamic, 2015) function of the type

\[ P(k) = Ak^{-B} \] (2.12)

- exponential function of the type

\[ P(k) = Ae^{-Bk} \] (2.13)

where \( A \) and \( B \) – parameters and \( k \) – the number of lines servicing a stop.

Based on a comparison of the two functions – power-law and exponential - used to fit the empirical values, the following conclusions were drawn:

(i) In contrast to some of the results reported about other cities whose PTNs seemed to be scale-free with a power-law decay of the number of stops as a function of the number of routes passing through them, it was found that the probability distribution of the stops as a function of the number of bus lines servicing each stop could be satisfactorily described by an exponential law, which is an indication of the lack of the BA model’s preferential attachment mechanism specific for scale-free
networks. Therefore, like Xu, Hu, Liu F., and Liu L. (2007); Chen, Li, and He (2007); and Yan and Wang (2009), our finding that P(k) follows an exponential distribution means that the stops in the PTN are attached at random;

Table 2.1. Derived regression equations with their estimated parameters

<table>
<thead>
<tr>
<th>PT Network</th>
<th>Method</th>
<th>Function</th>
<th>Type</th>
<th>Parameter</th>
<th>Value</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lines</td>
<td>Curve estimation</td>
<td>P(k) = Ak^B</td>
<td>Power</td>
<td>A</td>
<td>2.025</td>
<td>0.856</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.249</td>
<td></td>
</tr>
<tr>
<td>All modes</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>2.035</td>
<td>0.858</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.253</td>
<td></td>
</tr>
<tr>
<td>Bus lines</td>
<td>Non-linear fitting: Levenberg-Marquardt</td>
<td>P(k) = Ae^{-Bk}</td>
<td>Exponential</td>
<td>A</td>
<td>0.193</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.171</td>
<td></td>
</tr>
<tr>
<td>All modes</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td>0.196</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>0.174</td>
<td></td>
</tr>
</tbody>
</table>

than a power-law function leads to the conclusion that the PTN examined is neither random nor scale-free. Rather, it is a mixture between the two, which explains the presence of hubs, in Figure 2.12, that are not typical of exponential networks; the hubs, however, are not highly connected to the other nodes as in scale-free networks;

(iii) A comparison of the regression equations derived for the two cases, the whole network and the bus route only in Figure 2.12 show that these functions are almost identical in terms of the value of their coefficients, including the coefficient of determination, R-square. Therefore, the
contribution of the stops serviced by the routes of the two other transport modes – trains and ferries (approximately 5% of all routes, covering about 1% of the total number of stops) – does not significantly change the whole picture.

2.4.4 Examining PTN for “small-world” properties

In STEP 7, an export of the PTN was made in a ‘*.dat’ file containing the binary coded adjacency matrix $A$ in which, if there is at least one line serving a given stop, the matrix element formed by the intersection of the respective row and column (the start and end stop for a route segment) has a value of $a_{i,j} = 1$, otherwise $a_{i,j} = 0$. The ‘*.dat’ file created served as input for Pajek. In Pajek’s environment, this network was visualized either as being composed of sub-networks of the different modes of transport – bus, rail and ferry – forming the entire Auckland multi-modal network in Figure 2.13 or only as a bus-route network (BRN), including the stops serviced by the other operating modes, represented as disconnected nodes. Pajek plays a significant role as a complement of the Java program developed in performing network analysis and exploring the PTN structure and topological properties. In order to examine whether Auckland’s BRN exhibits “small-world” features, the following topological properties were calculated in STEP 8: average clustering coefficient, average shortest path length and average node degree. It is important to note that before the analysis is performed, the non-connected nodes (serviced by train and ferry routes) were excluded from consideration. For example, in the case of the bus-route network, the stops serviced by the two other operating modes – trains and ferries – although visualised, were excluded from the calculations conducted.

Figure 2.13. Auckland’s PT route network (all modes) as represented with Pajek
In the end in STEP 9, with the objective of ascertaining whether the observed BRN exhibited “small-world” features, the empirical values of the topological properties of the network examined are compared in Table 2.2 with their corresponding theoretical values generated with the same number of nodes and arcs of commensurable random network.

The examination of the whole PT network for “small-world” properties is not relevant, because this network consists of sub-networks of the different modes of transport (bus, rail, ferry) without arc connection between their stops.

Table 2.2. BRN in Auckland compared to random network generated with Pajek

| Public-transport mode | Network examined | Network Parameter/Property |  |  |
|----------------------|------------------|---------------------------|-----------------------------|
|                      |                  | Nodes | Arcs | Average Node Degree | Network Clustering Coefficient | Average Path Length |
| Buses                | Route network    | 6039  | 8937 | 2.96              | 0.052312             | 29.13               |
|                      | Random (Erdős and Rényi) network |  |  |  | 0.000397             | 17.25               |

Although the BRN shows an empirical value for clustering coefficient higher than the theoretical coefficient in a random graph, the average path length is longer (owing to the representation of the network as a directed graph), which differs from the definition of “small-world” graphs – "A small-world graph is a large-n, sparsely connected, decentralized graph \( n \gg k_{\text{max}} \gg 1 \) that exhibits a characteristic path length close to that of an equivalent random graph \( L \approx L_{\text{random}} \), yet with a clustering coefficient much greater \( C \gg C_{\text{random}} \)" (Watts, 1999).

It is obvious from the value of the average path length, shown in Table 2.2 for the bus-route network, that in order to travel between each two pairs of bus stops (origin point and destination points) the least number of sections (arcs) that each passenger has to traverse is 29, which is a 28 bus stops, excluding the first and the last bus stop (terminal stations).

Along with the above network’s topological properties, such as the average clustering coefficient and average shortest path length, the developed computer program enables through extracting the information about all (or only bus) routes as an ordered sequence of stops, to calculate the average number of stops per route (35 stops per route within the whole network including all public-transport modes – bus, ferry and train, and 36 stops per route when considering bus-route network only).

The average number of stops along a route in a combination with the average shortest path length (calculated based on the connectivity of stops in accordance with the adjacency matrix) can be of a great interest to practitioners, as these data provide them with useful information about
network’s coverage in terms of routes. The following finding is based on the information that has already been obtained in the case study and the values calculated, namely the average number of sections along the average shortest path is 29 route sections, i.e., 28 intermediate stops as well as the average number of bus stops per route equal to 36 (or 34 stops excluding the terminal stations).

The finding about the current coverage with bus routes within the network is such that in order to make a trip between each pair of stops along the average shortest path (i.e., traversing the least number of intermediate stops) on average passengers will be optionally using approximately 0.82 (82 %) of the average route’s length (measured in terms of number of stops) or 0.81 (when measured in number of sections). The 82% is calculated using Equation (2.1).

It is to note that for applying the approach previously described through Equations (2.1) - (2.10) on a real-life case study, a complete and precise O-D matrix’s data is required. This opens the door for a further, more applied study, in which the performance measures, indicators and formulations developed in this work could be used.

2.5 Conclusions

This work examines the structure and topological properties of the public-transport (PT) network in Auckland, New Zealand, in particular the bus-route network, and develop a method for this examination. On the basis of large network and statistical data analyses incorporated into the method developed and applied, the following major conclusions are drawn:

The examined bus-route network is neither a scale-free nor does it exhibit all the features of “small-world” networks. Instead, it can be considered as a mixture of exponential and scale-free networks, which means that the evolution of the bus-route network in Auckland is a consequence of random rather than preferential attachment of newly opened stops. The observed bus-route network is highly clustered; because of its representation as a directed graph, however, it is characterized by long average shortest path length.

The empirical contributions of this work are threefold:

(i) The probability node-degree distributions, the regression equations empirically derived and the values of the PT topological characteristics can be used by practitioners when making decisions about re-structuring existing PT networks or designing prospective ones;

(ii) The developed software program automates and speeds up the process of extraction and processing of GTFS data of large-scale PT networks including examination and analysis of the topological properties of complex PT networks.
The method developed provides the possibility not only of examining existing PT networks for scale-free characteristics and revealing the presence of hubs (which is important particularly for scale-free networks, as although these networks are robust against random, i.e., accidental failures, they are highly vulnerable to targeted or coordinated “attacks”), but also of exploring network topology and discovering “small-world” features.

This method could be applied to extract and process updated GTFS data “feeds”, including updated or newly created timetables put into operation on the basis of changes in routes during the year. The only condition under which the method can be used to import and export processed GTFS data for other PT networks is that the accompanying text files must be filled out in the same way and written with the same designations and order of the fields within these files, thus providing the minimum data needed for the analysis; this will also avoid the need for further modifications within the software program;

(iii) The method, in its last step, enables not only to introduce new PT performance measures and indicators, but also to solve two operational tasks used in practice: (a) given the desired average route length to determine the proportion of the origin-destination (O-D) PT demand that can use direct routes without transfers and the share of trips requiring transfers, and (b) given the proportion, and amount, of the O-D PT demand requiring transfers to determine the required average route length.

The proposed method and the introduced performance measures and indicators connecting complex network science theory and PT operations planning open the door for further research work involved with real-world case studies with the purpose of examining vulnerability and fault tolerance of complex PT networks characterised with different topologies as well as redesigning PT route networks and performing network reconstruction analysis.
Network science (Börner, Sanyal, & Vespignani, 2007) or the science of networks has revealed more opportunities for researchers and scientists who work in different research areas. One of the first attempts for application of network science as a tool is made by Euler (1953) in the 18th century in resolving the well-known Koenigsberg seven bridges problem and De Solla Price (1965) who pictured the network of scientific papers through linking each published paper to the papers that are directly associated with it. While network science (NS) is based on graph theory, it is also comprised of methods and approaches rooted in other research fields. Basically, network science is a result of the convergence of many fields, such as network analysis (Boissevain, 1979), social network analysis (Wasserman & Faust, 1994; Wasserman, 1980; De Nooy, Mrvar, & Batagelj, 2005; De Nooy, Mrvar, & Batagelj, 2011) as well as physical (Barabási, 2013) and biological sciences (Lewis, 2009). Thus, by providing new tools, mechanisms, and improved methods, network science has enabled exploring, examining and analysing the existing variety of complex networks through evaluating their characteristics and properties in different ways. Recent findings show that NS made it possible to understand complex networks’ structure, topological properties and dynamics (Boccaletti, Latora, Moreno, Chavez, & Hwang, 2006; Newman, 2003). In this way, by revealing networks’ strengths and weaknesses, and thereafter, establishing directions to improving networks’ structure, NS has facilitated overcoming problems that have yet to be solved by applying existing methods.

Chapter 3, which is a continuation of the previous chapter, is practically oriented. It is focused on an application, on real-life case studies, of the NS approach, which extends the method proposed in chapter 2, with a purpose to examine and analyse the structure and the topological properties of two metro public-transport networks characterised with different topology as well as to perform network reconstruction analysis aimed to quantitatively estimate the impact of structural changes on networks’ features, the vulnerability of the studied network in case of a unexpected breakdown, and to evaluate the network’s efficiency from connectivity’s point of view.
3.1 Objectives and tasks of the case study

The objective of the case study presented in this chapter is to examine and analyse the structure and topological properties of real-world transportation systems on a case study by using an existing method uniquely combining computer programming techniques, implementation of known algorithms, large-scale network and data analysis. A network-science perspective was applied, while seeking to reveal network strengths and weaknesses. The results of this study can serve for improving PTNs and shed light on a further research.

In order to achieve the objective, the following essential tasks were completed:

(i) A review of the literature related to NS concepts and their practical applications;
(ii) Collecting, processing and analyzing data on a comparative case study;
(iii) Examining the structure, characteristics and topological properties of the observed PTNs by performing network and data analysis using the developed method; and
(iv) Drawing reasonable conclusions and outlining the possibilities for a further research work for improving public-transport networks’ functioning.

3.2 Literature review

As a continuously developing research field in recent years, significant progress has been made in network science (Börner, Sanyal, & Vespignani, 2007) with respect to its methods. Due to the opportunities it demonstrates in exploring and analysing network structures used to represent complex real-life systems, including PTNs, it has been of interest to scholars working in different research areas. Accordingly, it has been shown to be applicable in numerous studies and published research works.

As an object of much interest in recent years, complex systems have undoubtedly led to the appearance of considerable research based on graph theory and NS. Their principles are used for examining structure and topology (Lewis, 2009; Rodrigue, Comtois, & Slack, 2013 for a large variety of networks. These networks include social networks (Wasserman & Faust, 1994), the World Wide Web (WWW), Internet, as well as the network of PT modes – road, rail, sea, or air (Lin & Ban, 2013).

The contribution of Erdős and Rényi (1959, 1960), Gilbert (1959) and Bollobás (1998) to the theory and practice of random graphs is noteworthy. The work by Watts and Strogatz (1998) on small world networks (SWN) also warrants mention. They found that in terms of structural properties, networks were highly clustered, similar to a regular lattice, and had small, average network shortest path lengths (APL) characterizing random networks. Based on the analogy with the small world phenomenon (Milgram, 1967), also described as six degrees of separation (Guare,
Watts and Strogatz called these networks small world, thus directing the beginning of a myriad of studies towards exploring real life networks for small world properties. Newman (2000), discussing small world effect, found out that “the most important result is that small-world graphs show behaviors very different from either regular lattices or random graphs”.

In addition to the small world effect, one of the behaviours that may be of interest to researchers and practitioners is that real life networks exhibit features related to their functioning. For example, the node degree distribution (NDD) of WWW seems to indicate a power-law (Barabási & Albert, 1999; Adamic & Huberman, 2000).

In the last two decades, the contribution of Barabási and Albert (1999), marked by their findings for scale-free networks have been significant for network science. As a result of examining the topology of large and diverse networks, they concluded that “independent of the system and the identity of its constituents, the probability $P(k)$ that a vertex in the network interacts with $k$ other vertices decays as a power-law, following $P(k) \sim k^{-\gamma}$", where the exponent $\gamma$ is called a scaling factor. Moreover, Barabási and Albert proved that the widely used network models, also known as Erdős and Rényi (ER) and Watts and Strogatz (WS), failed for two important features of real life networks – growth and preferential attachment. On the one hand, in ER random graphs, the number of vertices $N$ is fixed, and each pair of vertices is connected to a given probability $p$. The values of the probability with which any vertex has $k$ edges are distributed following Poisson’s probability distribution. On the other hand, in compliance with WS model, SWNs have $N$ nodes forming a one-dimensional lattice within which each node is connected to two other nodes – the nearest one and the next nearest – with a probability $p$, where the value of $p$ is selected randomly. The probability $p$ is exponentially distributed, which means that highly connected vertices, i.e., vertices having large values of $k$, are in practice absent. This is outlined as an important feature of both ER and WS models. As opposed to the latter, the findings of Barabási and Albert showed that the probability $P(k)$ of a given vertex having $k$ neighbours decays following a power-law distribution, which means that it is more likely that highly connected vertices will occur in these networks, called scale-free networks.

In order to demonstrate that power-law scaling requires the presence of both growth and preferential attachment simultaneously, Barabási and Albert developed two models (Barabási & Albert, 1999). One is known in the literature as, (i) Albert’s growth model (A), which supports the network’s growth, but the attachment of a new node to the network is not preferential. Rather, it is uniform (i.e., each new vertex connects to the existing vertices with equal probability). The other model is (ii) Barabási’s preferential attachment model (B), in which the number of vertices is fixed (i.e., there is no growth), and the attachment is made preferentially (it is more likely that a new
vertex connects to a highly connected vertex which causes the occurrence of a phenomenon referred to as “rich-get-richer.”). Finally, they combined both models, B and A, in the renowned Barabási-Albert (BA) model (Albert & Barabási, 2002) characterized by growth and preferential attachment. Generalization with respect to the most significant findings regarding SFNs and SWNs obtained based on studies related to exploring complex real networks is made by Barabási and Bonabeau (2003).

Apart from the aforementioned studies, it is noteworthy that with their work on network efficiency, Latora and Marchiori (2001) subsequently continued with a practical application for evaluation of local and global efficiency of a real life PTN (Latora & Marchiori, 2002) with added value for network science. In contrast to Watts and Strogatz (1998) who used an average network’s clustering coefficient (CC) and an average network’s shortest path length (APL) to examine small world properties of networks, Latora and Marchiori (2001) introduced the term efficiency - a measure showing the extent to which information can be exchanged within a given network. The major finding of their works is that the main underlying principle characterizing the structure of all the networks examined is the small world principle.

Newman (2003) followed by Boccaletti, Latora, Moreno, Chavez, and Hwang (2006) conducted exhaustive reviews of a myriad of studies summarising the most significant research work. They discuss the main concepts, definitions and method in the field of NS and graph theory as well as their application to represent, examine and model complex networks and evaluate their parameters.

Barthélemy (2011) conducted a thorough review on real-world spatial networks, such as transportation, infrastructure, mobility, neural as well as complex networks, the latter characterised with small set of parameters some of which (such as the degree distribution) are not applicable for spatial networks. Barthélemy, in his work, discusses transportation networks and highlights their spatial nature. He is describing the different approaches used to represent transportation networks (L-space, P-space topology, etc.) as well as reviewing a large number of research works to examine the properties of real-world spatial transportation networks and public-transport networks in particular.

In order to evaluate PTN robustness, Rodríguez-Núñez and García-Palomares (2014) developed a methodology enabling measuring PTN vulnerability through the impact of random and targeted attacks causing disruption of network links, which resulted in travel time losses. The authors found that the impact of targeted attacks on passengers’ travel time losses is greater than the impact of a breakdown of randomly attacked links.
Dimitrov and Ceder (2016) developed a method enabling to examine and analyse complex public-transport networks through combining computer programming, network and statistical data analysis techniques. The application of the method on a case study is described in Chapter 2.

In contrast to previous studies on the robustness of PTNs where vulnerability is measured through reliability of connections from a network topology point of view, Cats and Jenelius (2014) developed a dynamic and stochastic notion of PTN vulnerability which uses the dynamics and interaction of supply (vehicles) and demand (passengers) to evaluate the impact of network disruptions (the inability of vehicles to continue along the route or to enter a disrupted link). To be able to perform network vulnerability analysis, the authors extended the betweenness centrality measures to Network Centrality, Centrality for vehicles and Centrality for passengers. They applied these measures for the high-frequency public transport network of Stockholm, Sweden, to identify candidate important links (from the operator’s and passengers’ perspectives) for which any disruption would have strongest impact. To mitigate the effect of network disruptions on passengers, real-time information (RTI) was provided in the simulation scenarios, which allows passengers to make an informed decision when choosing alternative routes. The case study revealed that the impacts of service disruptions depend on the demand’s reaction to supply’s variations caused by these disruptions. The results of the vulnerability analysis showed that (i) “link centrality does not necessarily imply link importance as measured by its impact on total welfare” and (ii) importance of links is a function of the information provided to passengers, which in turn depends on the RTI that varies for the examined disruption scenarios and may, as found in one of the scenarios, even worsen the effect of the disruptions. The proposed heuristic approach (Cats & Jenelius, 2014) for identifying important links has found practical application in a later study conducted by Cats and Jenelius (2015) in which they proposed a methodology enabling evaluating the effect of link capacity increase as a measure to mitigate the impact of unexpected (unplanned) network disruptions. The evaluation method which was demonstrated on the rapid PTN of Stockholm, Sweden, as a case study, considering short-term and unexpected disruptions, was implemented in two stages: (i) identifying a set of important links in the network and (ii) evaluation of a set of capacity enhancement schemes for each of the important links (i.e. an increase of the capacity of one or more public transport lines) and a selection of the most effective scheme based on its impact on welfare changes. Cats (2016), continuing previous studies, examined the robustness of PTN under link failures. Cats developed a method allowing for evaluating the robustness of alternative networks through the application of a full-scan approach and under different range of disruption scenarios, each corresponds to a single link’s failure. The method proposed allows for the estimation of the impact of a link’s failure on passengers’ travel time for a given network’s alternative and the robustness value of a network’s alternative assessed through a comparison
between travel time losses. The impact of a link’s disruption is measured by the delayed passengers. In a subsequent study, Malandri, Fonzone, and Cats (2018) proposed a method enabling evaluating the vulnerability of PTN. The aim of their study was to identify the effect of a link closure on the passenger flow redistribution across the network as well as to perform analysis of passenger flows enabling detection of the most overloaded links and establishment of whether the supply can meet the variable (reallocating) passenger demand. The proposed approach was demonstrated on disruption scenarios simulating an unplanned closure of central corridors serving the rapid transit network of Stockholm. The vulnerability of the network was evaluated as the difference of the volume over capacity ratio in the disrupted and the base case. The results from the method’s application showed that (i) “the impact of disruptions on passenger flow distribution last up to 6 times longer than the service closure time” and (ii) link disruptions impacted locations standing 10 to 15 km away from the place of the disruption.

The literature review conducted, encompassing fundamental and recent research in the domain of network science, spatial networks, complex networks, transport geography, and public transport in particular, enabled drawing the following main conclusions:

- The limitations of the existing approaches and tools for analyzing real-life complex networks, such PTNs, place a number of new challenges for researchers and scholars in terms of the data required, methods to be applied, and software to be used.
- Through combining recent findings of other fields of research, NS enables exploring, examining, analyzing, modelling and simulating real-life complex networks.
- Theories related to NS and the findings of complex systems are a good foundation for practical studies of the structure of real-world networks (including PTNs) through an evaluation of topological properties such as CC, APL, NDD and network efficiency (local and global).

3.3 Case study

3.3.1 Data collection and data processing

The objects of examination in this case study were the subway (metro) networks in Washington DC (USA) and Oslo (Norway). The first of the observed public transport metro networks in Washington DC, WMN, (see Figures 3.1.a and 3.1b) is composed of 91 metro stations serviced by six lines traveling between the terminal stations and the second of the observed metro networks in Oslo, OMN, also known as T-bane or Oslo Tunnelbane (Fig 3.2) is composed of 101 metro stations serviced by five lines traveling between the terminal stations. It is interesting to mention that only 17 out of 101 of the stations in the Oslo’s metro network are underground or indoors7.

7 https://en.wikipedia.org/wiki/Oslo_Metro
3.3.2 Examining the subway network for small world properties

Because of differences in data formats and descriptions used by the public transport operators within the GTFS feeds\textsuperscript{8}, in contrast to Chapter 2 where the required GTFS data was extracted and processed by means of a Java program (Dimitrov & Ceder, 2016), the data of this work feeds in the form of text (‘*.txt’) files. The GTFS\textsuperscript{9,10} data, provided by the Washington Metropolitan Area Transit Authority as well as by the Ruter – the management company that plans, coordinates, orders and markets public transport in Oslo, was directly imported and further processed within the Microsoft Excel\textsuperscript{®} working environment. As a result, useful information regarding the subway stations has been extracted, such as station names, codes (an identifying number), geographical coordinates (latitude and longitude) and the sequence of stations along each of the metro lines in the examined networks. Then, the data about the connections between each pair of stations have been further used in order to assign values in the Excel adjacency matrix \{a_{i,j}\} showing the connectivity between each two nodes within the network, i.e., between each two subway stations. For example, if station $I$ is directly connected by link (railway section) to station $j$, then the matrix element $a_{i,j} = 1$, otherwise $a_{i,j} = 0$. As a result, the subway network examined is represented as an undirected, unweighted graph within which each node represents a subway station (in this network the number of stations in both directions is the same and these stations are located opposite one another) and the edges (having length 1) represent the connection between two stations. The presence of a link between two stations means that there is at least one subway line servicing these stations. A flowchart of the algorithm applied for the purpose of processing the GTFS data is shown in Fig. 3.3 below.

\textsuperscript{8} https://developers.google.com/transit/gtfs/#overview-of-a-gtfs-feed
\textsuperscript{9} http://transitfeeds.com/p/wmata/75
\textsuperscript{10} http://transitfeeds.com/p/ruter/240
(a) Metro system map, adapted from Washington Metropolitan Area Transit Authority

(b) Planned improvements, adapted from Momentum

Figure 3.1. Washington DC Metro system map

11 wmata.com/pdfs/pocket_guides/english.pdf
Figure 3.2. Oslo Metro system map

Figure 3.3. Flowchart representing the sequence of steps outlining the logic of the proposed approach for examining and analysing PT (subway/metro) networks
3.3.2.1 Evaluation of the average network’s shortest path length and the average network’s clustering coefficient

The information extracted from GTFS files and saved in a MS Excel file is thereafter imported into a developed Java software program automating and accelerating the processing of the data. Within the Java program, the imported adjacency matrix data is then processed, transformed, and as a result exported and saved into a (*.dat) file that served as an input into the program for large scale network analyses Pajek\(^{14}\) (De Nooy, Mrvar, & Batagelj, 2005; De Nooy, Mrvar, & Batagelj, 2011) which was used to visualize the network and perform further analyses. By using Pajek program, topological properties of the examined network, such as average network shortest path length (appearing below as an average path length, APL), average network clustering coefficient (appearing below only as clustering coefficient, CC) and average network’s node degree (ANND), have been computed. Alternatively, apart from Pajek, the average shortest path length for undirected graphs was calculated within the Java software program developed by using the following formulae (Prettejohn, Berryman, & McDonnell, 2011):

\[
L = \frac{2}{N(N-1)} \cdot \sum_{i=1}^{N} \sum_{j=i+1}^{N} d_{i,j}
\]

(3.1)

where: \(L\) is APL, \(N\) – number of nodes (stations) in the network, \(d_{i,j}\) – the shortest path (in terms of number of sections) between any two pairs of nodes \(i\) and \(j\), and \(d_{i,j} = d_{j,i}\).

Formula (3.1) was incorporated within the Java program not only to calculate the average network shortest path length as a number of consecutive route sections, but also in kilometres by substituting in \(d_{i,j}\) the distances between stations along the shortest paths computed through the Java implementation (Lau, 2006) of Floyd’s shortest path algorithm (Floyd, 1962). As shown later in this chapter, in order to verify the output results of the software program developed, the value of the APL (in number of sections) calculated with the Java program was compared with the APL computed by Pajek. In order to discover whether the examined metro networks visualized within Pajek’s working environment (Figures 3.4a and 3.5a) exhibit small-world properties, their topological properties have been compared (see Table 3.1 and Table 3.2) to those of random Bernoulli/Poisson (De Nooy, Mrvar, & Batagelj, 2011) networks generated with Pajek (Figures 3.4b and 3.5b) using the same number of nodes and average network node degree as an input, as did Watts and Strogatz (1998).

\(^{14}\) http://Pajek.imfm.si/doku.php?id=pajek
Figure 3.4. Washing DC’s metro network compared with a random network

Figure 3.5. Oslo metro network compared with a random network

Table 3.1. Washington DC’s metro network compared with a random network generated with the Pajek program

<table>
<thead>
<tr>
<th>Public transport mode</th>
<th>Networks</th>
<th>Network properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nodes</td>
</tr>
<tr>
<td>Subway/Metro</td>
<td>Examined subway/metro network</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Generated random (Bernoulli/Poisson) network</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 3.2. Oslo’s metro network compared with a random network generated with the Pajek program

<table>
<thead>
<tr>
<th>Public transport mode</th>
<th>Networks</th>
<th>Network properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nodes</td>
</tr>
<tr>
<td>Subway/Metro</td>
<td>Examined subway/metro network</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Generated random (Bernoulli/Poisson) network</td>
<td>105</td>
</tr>
</tbody>
</table>
The results of the above comparison between the empirical (calculated) and the theoretical (generated) values of the topological properties – network’s average shortest path length \( \text{APL}_{\text{ESN}} \) and \( \text{APL}_{\text{RN}} \) and network’s average clustering coefficient \( \text{CC}_{\text{ESN}} \) and \( \text{CC}_{\text{RN}} \) for the examined (metro) and the generated (random) networks, respectively, show that:

- The average path lengths within the examined Washington DC’s metro network \( \text{APL}_{\text{ESN}} = 11.51 \) sections against nearly two times less \( \text{APL}_{\text{RN}} = 5.06 \) in the random network) and within the Oslo’s metro network \( \text{APL}_{\text{ESN}} = 14.68 \) sections against nearly two and a half times less \( \text{APL}_{\text{RN}} = 5.80 \) in the random network) show that the average distance between the origin and destination points in the first network (WMN) along the shortest path is 12 sections on the average or 11 subway stations (the number of sections minus 1) and for the second network (OMN) - 15 sections on average and 14 metro stations, respectively. In other words, according to the definition of the average path length (Prettejohn, Berryman, & McDonnell, 2011), the above value can be interpreted as follows: the average number of sections that must be transferred along the shortest path between any pairs of stations in the networks is 12 railway sections on the average along the Washington’s DC metro network and 15 sections along the Oslo’s metro network;

- The value of the clustering coefficient for both the examined real-world metro networks is 0, i.e. \( \text{CC}_{\text{ESN}} = 0 < \text{CC}_{\text{RN}} = 0.0156 \) (for WMN) and \( \text{CC}_{\text{ESN}} = 0 < \text{CC}_{\text{RN}} = 0.0718 \) (for OMN). That zero value means that within both the networks examined there is no node (station) that has neighboring stations connected to each other through a link.

Based on the above results, it can be concluded that both the metro networks examined, for Washington DC’s and Oslo, characterized by average path lengths of 11.51 and 14.68 sections, respectively and both having clustering coefficient of 0, cannot be considered small world networks. This is because the derived values differ from what is given as a definition for small world graphs (Watts, 1999): “A small-world graph is a large-n, sparsely connected, decentralized graph \( (n >> k_{\text{max}} >> 1) \) that exhibits a characteristic path length close to that of an equivalent random graph \( (L \approx L_{\text{random}}) \), yet with a clustering coefficient much greater \( (C >> C_{\text{random}}) \).”

### 3.3.2.2 Evaluation of network efficiency

In contrast to Watts and Strogatz (1998), examining real life networks by using average path length (as a global property) and clustering coefficient (as a local property), Latora and Marchiori (2001) introduced the concept of network efficiency – global and local – in their work, measuring the communication between the nodes within a network. In this way, they examined networks’ local and global behaviour with local efficiency \( E_{\text{loc}} \) and global efficiency \( E_{\text{glob}} \) instead of using CC and APL. Therefore \( E_{\text{loc}} \) and \( E_{\text{glob}} \) replace CC and APL. It is known (Latora & Marchiori, 2001) that small world networks have both high \( E_{\text{loc}} \) and \( E_{\text{glob}} \).
As the efficiency \( \varepsilon_{i,j} \) between nodes \( i \) and \( j \) is inversely proportional to the shortest path \( d_{i,j} \) between these two nodes (Latora & Marchiori, 2002), i.e.:

\[
\varepsilon_{i,j} = \frac{1}{d_{i,j}}
\]  

the global efficiency \( E_{glob} \) was calculated via the following formulae implemented in the Java program developed:

\[
E_{glob} = \frac{2}{N(N-1)} \cdot \sum_{i=1}^{N} \sum_{j=i+1}^{N} \varepsilon_{i,j} = \frac{2}{N(N-1)} \cdot \sum_{i=1}^{N} \sum_{j=i+1}^{N} \frac{1}{d_{i,j}}
\]  

\( E_{glob} \) takes values within the range \( 0 \leq E_{glob} \leq 1 \) (Latora & Marchiori, 2001), i.e., \( E_{glob} \in [0;1] \). Ideally, the global efficiency, considered (Latora & Marchiori, 2002) as the efficiency of the whole network, would have the value of \( E_{glob} = 1 \), which could be valid in complete graphs in which between each pair of nodes there is an edge connecting them.

The results showing that the global efficiencies for both the metro networks having values \( E_{glob} = 0.14 \) (Washington DC) and \( E_{glob} = 0.12 \) (Oslo) means that these networks have only 14\% and 12\% of the efficiency of the ideal one (\( E_{glob} = 1 \)), the latter having a direct line from each station to the others. The obtained low values are an indication of poor global efficiency of the networks, lacking direct connections between their stations.

The global efficiency of the first (WMN) of the observed networks was also evaluated using the physical distances between the stations (considering the network as a weighted graph) as opposed to the distances between stations with length of \( l \) (when the network was considered an unweighted graph). In order to calculate the global efficiency \( E_{glob} \):

- Firstly, by using stations’ geographical coordinates, the distances between each pair of metro stations directly connected with an edge were calculated by means of the well-known haversine formula\(^{15}\) implemented in MS Excel and then put into the matrix of distances \( \{l_{i,j}\} \);

- The distances calculated between the stations in the filled matrix of distances served as an input into Floyd’s shortest path algorithm implemented into the Java program developed. As a result, the value \( APL = 17.61 \) km has been calculated by using the physical distances between the metro stations being quite close to the real distances between these stations (or they coincide in the case in which these distances are measured between two stations located on a straight section);

- The evaluated global network’s efficiency is \( E_{glob} = 0.11 \). In contrast to the first case in which the global efficiency \( (E_{glob} = 0.14) \) was calculated using the shortest paths’ lengths (the least number of sections) between the stations found due to the information from \( \{a_{i,j}\} \), in the

\(^{15}\) https://en.wikipedia.org/wiki/Haversine_formula
second case the efficiency was computed based on the shortest distances (in kilometers) between each pair of stations calculated using information from the matrix of the physical distances \( \{l_{i,j}\} \) between the stations. The latter were computed by stations’ geographical coordinates. The low value of the global efficiency \( (E_{glob} = 0.11) \) showed that the examined network is 0.89 less efficient than the ideal network \( (E_{glob} = 1) \) in terms of the lack of direct connections between the stations, and thus it appears to be globally poor. As the global efficiency does not take into account the route of the metro lines as well as the passenger trips, a less efficient network does not necessarily mean that the network is unable to serve the existing PT demand. Instead, the low global efficiency values only show that possible network improvements could be achieved in network’s topology (and not by the level of service it provides) through the construction of new links (sections), as long as it is proven that the cost incurred for this would be justified. This, however, is a subject of consideration of the respective operator in compliance with the perceived planning strategy and government’s policy – matters not addressed in this case study, and hence, not discussed in this chapter.

Since the network analyses, performed with the software program Pajek for the metro networks studied, established that they are not clustered at all \( (CC = 0) \), the alternative topological property of the clustering coefficient (which is the local network’s efficiency \( E_{loc} \)) was not evaluated. Again, the value 0 of CC means that there are no metro stations within the networks having neighbouring stations connected to one another. Therefore, it can be concluded that the networks examined are not fault tolerant in the context that each disruption (disconnected stations) would significantly affect the transport service as there are no alternative connections between the stations. This leads to the conclusion that the higher the number of connections in the networks, the greater the fault tolerance of the networks. This can be achieved by increasing connectivity between stations in the network through constructing more sections linking important subway (transfer) stations – hubs.

The Washington Metropolitan Area Transit Authority’s (WMATA) strategic plan\(^{16}\) for 2013-2025 discusses constructing a rail track (section) that would serve as a connection between the Blue and Orange/Silver metro lines (see the Blue line’s Arlington Cemetery station and the Silver/Orange Court House station as shown on Figure 3.1b), as one of two potential alternatives. This would be a new edge within the existing subway network enabling passengers to make one seat (non-transfer) trips between Dulles Airport, Tysons Corner, Ballston, The Pentagon, National Airport, and the Alexandria metro stations, thus avoiding the need to travel through the core of the network. Both alternatives would result in an increase of train frequency with five more trains per hour, thus leading to an increase in the vehicle carrying capacity provided for up to 4000 passengers.

\(^{16}\) https://www.wmata.com/momentum/momentum-full.pdf
per direction per hour. People from WMATA expect the above measures to reduce the average passenger waiting time by an average of three minutes for around 16000 trips.

For the purpose of exploring how the above constructive changes planned for the subway network would affect the APL, CC, and the network’s (global) efficiency, the newly created link was added as an edge into the adjacency matrix \( \{a_{i,j}\} \), then the steps described in Sections 3.2.1 and 3.2.2 were applied. As a result, the following values of the evaluated topological properties of the network examined were identified: \( \text{APL} = 11.32 \) sections in the proposed network as opposed to 11.51 for the existing network, and clustering coefficients, 0.0252 as opposed to 0, respectively. The network efficiency remains unchanged (0.14). Even after the expected changes, the network is still not SWN as it has a clustering coefficient \( CC_{\text{ESP}} = 0.0252 \) commensurate to that of the RN \( CC_{\text{RN}} = 0.0156 \) and still quite long \( \text{APL} \) (11.32 sections) compared to that value for RN (5.06). Thus, as expected, the structural change above (only one new link added) does not globally affect network connectivity. Although the APL is slightly reduced from 11.51 sections to 11.32 on the average (1.65 % decrease), the global efficiency values are still at the same low level (0.14). The positive effect on the network can be felt locally as the increased value of CC from 0 to 0.0252 means that the network would become more faults tolerant. This means that in an event of a breakdown (a disconnected link in the triangle Arlington Cemetery, Court House and Rosslyn), the network would still be functioning because of the presence of an alternative (a newly constructed) connection. It would also be of interest to the operator to estimate how a newly created link would affect the number of trips without transfers and what the value of the transfer coefficient would be. This task is beyond the scope of this case study and it could well be a subject of further research.

3.3.3 Examining the subway network for scale-free properties

3.3.3.1 Data analysis

Based on the GTFS data processed regarding the metro stations and the metro lines in the two networks (see Figures 3.6 and 3.7) it is evident that the majority of the stations (76 stations) in the first (Washington DC’s) network are serviced by only one metro line (48 stations) or two metro lines (28 stations). There are also 13 more stations serviced by three lines. On the other hand, there are only two stations serviced by four and five subway lines, respectively, that can be considered hubs. Thus, the network topology of the metro network examined resembles the topology of scale-free networks in which most of the nodes have a small number of links, with only a small number of nodes (called hubs) having multiple connections (Barabási & Bonabeau, 2003), which is in contrast with the second examined metro network in Oslo. Similar to the Washington’s metro network, the majority of the stations in the Oslo’s metro network (89 stations) are also serviced by one metro line (61 stations) or two lines (28 stations). However, Oslo’s network does not have small number
highly connected stations (hubs). Instead, it is characterised with 3 stations serviced by 3 lines, another 3 stations serviced by 4 lines, and 6 more stations serviced by 6 metro lines. For the sake of clarity, the 5th line of the Oslo’s metro network (in green) can be considered as composed of two separated lines as it runs twice through nine stations and follows two separate routes. That is, when a vehicle runs in the direction from Vestli to Sognsvann (see Figure 3.2), it can either pass through the station “Ullevål stadion” and continues to station Nydalen (the first route), or continues in the direction station Berg.

![Bar chart](image1.png)

*Figure 3.6. Distribution of the Washington DC metro stations according to the number of lines k servicing a station.*

![Bar chart](image2.png)

*Figure 3.7. Distribution of the Oslo’s metro stations according to the number of lines k servicing a station.*

With the intention of confirming or falsifying the above supposition, in order to estimate the probability $P(k)$ with which a randomly selected station is being serviced by $k$ lines, two types of functions – a power-law (Adamic, 2000; Newman, 2005) and exponential – were approximated
through performing a statistical data analysis (Kirkup, 2002) as shown in Table 3.3 (for Washington DC’s network) and Table 3.4 (for Oslo’s network) in Appendix A. It is obvious (from Table 3.3) that the coefficient $A$ in the power function has a value close to 1, i.e.: $A \approx 1$. Therefore, it can be accepted that the formula $P(k) \sim k^{-B}$ satisfactorily represents the established statistical relationship between $P$ (the dependent variable) and $k$ (the independent variable), i.e., $P(k) \sim k^{-2.62}$ in which the scaling factor $B$ falls within the range $2 < B < 3$ (Barabási & Bonabeau, 2003). Based on this result, it can be accepted that the examined network exhibits characteristics of scale-free networks. On the other hand, as is illustrated on Figure 3.8, the results of the least squares fitting procedure performed for the empirical values also revealed that the observed nonlinear relationship between $P$ and $k$ is better fitted by means of an exponential ($R^2 = 0.903$) rather than a power-law function ($R^2 = 0.814$). From Figure 3.9 one can observe that in contrast to the Washington DC’s metro network, the one of Oslo does not exhibit the specific characteristics for scale-free networks, that is, small number highly connected nodes and the probability $P(k)$ is not satisfactorily described by a power-law function $P(k) \sim k^{-B}$. Therefore, it does not appear that the studied metro network of Oslo is a scale-free network.

**Table 3.3. Derived regression equations with their estimated parameters for the metro network in Washington describing the probability distribution of Washington’s DC metro stations in function of the number of metro lines $k$ servicing a station**

<table>
<thead>
<tr>
<th>PT network</th>
<th>Method</th>
<th>Function</th>
<th>Type</th>
<th>Parameter</th>
<th>Value</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway lines</td>
<td>Least squares fitting</td>
<td>$P(k) = A.k^{-B}$</td>
<td>Power</td>
<td>$A$</td>
<td>0.949</td>
<td>0.814</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B$</td>
<td>2.620</td>
<td></td>
</tr>
<tr>
<td>Subway lines</td>
<td>Least squares fitting</td>
<td>$P(k) = A.e^{-B.k}$</td>
<td>Exponential</td>
<td>$A$</td>
<td>2.149</td>
<td>0.903</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B$</td>
<td>1.11</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.4. Derived regression equations with their estimated parameters for the metro network in Oslo describing the probability distribution of Oslo’s metro stations in function of the number of metro lines $k$ servicing a station**

<table>
<thead>
<tr>
<th>PT network</th>
<th>Method</th>
<th>Function</th>
<th>Type</th>
<th>Parameter</th>
<th>Value</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway lines</td>
<td>Least squares fitting</td>
<td>$P(k) = A.k^{-B}$</td>
<td>Power</td>
<td>$A$</td>
<td>0.505</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B$</td>
<td>1.656</td>
<td></td>
</tr>
</tbody>
</table>
3.3.3.2 Interpretation and discussion of results

Regardless of the fact that for the Washington DC’s metro network examined the presence of a small number of highly connected nodes (considered hubs) was established, and that a power-law function satisfactorily describes the node degree distribution of that network, it still cannot be considered a purely scale-free network. The fact that the examined network is better described by an exponential rather than a power-law function supports this statement. As Barabási and Albert
(1999) wrote, “a common feature of the ER and WS models is that the probability of finding a highly connected vertex (that is, a large \(k\)) decreases exponentially with \(k\); thus, vertices with large connectivity are practically absent.” Accordingly, “such networks are called the exponential networks” (Chen & Shi, 2004). It is known (Albert, Jeong, & Barabási, 2000) that in RNs, each node has approximately the same number of links, which means that the node degree \(k_i\) of each node \(i\) is close to the average network’s node degree \(\langle k \rangle\), i.e. \(k_i = \langle k \rangle\). In the case study the network was presented as of bus-station network which “retains the basic topological features of public transportation networks” (Lu & Shi, 2007). In this network the average node degree having a value of 1.67 lines servicing each node is on the average 2.4 and 3.0 times less than the degree of the two highly connected nodes in the network (serviced by four and five subway lines, respectively). Therefore, due to the presence of hubs, the network also cannot be considered as an entirely random network. According to Albert and Barabási (2002) who wrote that “if all processes shaping the topology of a certain network are properly incorporated, the resulting \(P(k)\) often has a rather complex form, described by a combination of power laws and exponentials”, it can be expected that the network examined should have a complex form, which shows that the PTN examined can be considered a complex network. The latter is not valid for the metro network in Oslo as the \(P(k)\) is neither good fitted by an exponential nor by a power-law function. In accordance with Albert and Barabási who wrote that the “evolving networks can develop both power-law and exponential degree distributions” (Albert & Barabási, 2002) as the network examined can satisfactorily be described by a power-law as well as by exponential functions, it can be expected for it to be an evolving network.

### 3.4 Conclusion

The results of the examination of two real life metro networks and the analyses performed as part of this case study, performed through the application of the proposed method utilising NS concepts and tools, have led to a few general conclusions that can be summarized as follows:

The network analysis performed in exploring the topological properties of the Washington DC’s and the Oslo’s metro networks showed that when represented in an L-space network topology, the networks examined do not exhibit small-world properties, and hence, they are not small-world networks.

The examination of the Washington DC’s metro network and its analyses also showed that the network is neither a scale-free nor random network; this is based on the consideration of network’s node degree distribution, the number of the metro lines servicing each station and representing the network as a bus station network. In contrast to the Oslo’s metro network, the metro network in Washington appears to be a complex network.
The analysis considering the networks’ global efficiency, performed by using network science concepts and findings, showed that both the metro networks examined appear not to be faults tolerant. In case of a railway section’s breakdown, this would significantly affect the quality of the transport service provided, because of the lack of alternative connections linking the disconnected metro stations. These results illustrate connectivity weaknesses, thus indicating that there is a room for improving the connectivity between the stations within the networks.

This case study does not only examine real-world metro networks with their topological properties, but also performs network’s reconstruction analysis for the Washington DC’s network. That is, it considers a hypothetical construction of a section connecting two stations within the Washington DC’s network to show that a new link would not sensibly improve the global network’s efficiency; this is explicated by measuring the presence of direct connections between the metro stations of the network.

It turned out that both the metro networks examined have low valued global network’s efficiencies. This global efficiency does not take into account the routes of the operational metro lines and the passenger trips; thus, the above statement does not necessarily mean that these networks are inefficient in serving passengers and covering the existing PT demand.

The results attained using the method could be used to examine the impact of a newly created link on the public transport network in terms of the number of direct trips and trips with transfers before and after the creation of the link. The latter would reveal new opportunities to improve the public transport network structure and operation’s efficiency from both the users and operator’s perspectives.

Once the network science concepts and tools, and the proposed in Chapter 2 method in particular, were applied to examine and establish what the public-transport network’s topology is, what the network’s topological properties are (as was done in Chapter 2 for Auckland’s PTN and in Chapter 4 for Washington DC’s and Oslo’s), and how efficient and fault tolerant the network is from Networks science’s point of view (as done for WMN and OMN in Chapter 4), it is worth, from a public-transport operations’ perspective, considering data of the actual public transport demand, bus loads (vehicle capacity utilisation) and frequency in a multi-agent system in which passengers, vehicles and cars interact with each other – a subject considered in detail and presented in the next Chapter 4.
This chapter is derived in part from an article published
in Transportation Planning and Technology on 19th of April 2017,

Over the past decades, urban traffic issues have presented growing concerns. Indeed, the increased volume of urban traffic adversely affects large cities by causing traffic jams especially at peak-hours, increased noise levels, and air pollution of the surrounding environment. In order to reduce these negative effects, local public authorities may rely on and fund a PT system by which they can provide the urban population with an adequate transport service for satisfying their mobility needs. Designing PT systems to satisfy a variably increasing travel demand, which will provide passengers with a developed PT network and frequency of service in a cost-effective manner is a challenging task.

Auckland is the economic capital of New Zealand, the seventh most motorized country per capita on the planet (The World Bank, 2014). In 2013, Auckland Region was home to more than 1.4 million inhabitants – more than one-third of New Zealand’s population. In Auckland Region, more than 18% of the population has access to three or more motor vehicles, and only 6.5% of the inhabitants use Auckland’s PT for work trips (Statistics New Zealand, 2013). Thus, the congestion on roads leading to Auckland’s Central Business District (CBD), primarily due to commuting during morning and evening peak periods, is systematic. The perpetually increasing population is a major consideration for transit planners while requiring that PT service be made more attractive to Aucklanders in order to encourage use of PT over the use of private cars. Subsequent questions which beg asking to relate to the measures to be taken by PT operators and agencies, and how they would react to an increase/decrease of PT-share so as to provide PT users with a reliable and more convenient PT in the future.

This chapter responds to the above questions through modelling and simulation of the passengers’ transportation process as a multi-agent system (MAS) composed of agents, such as bus drivers, buses, private car drivers, cars and passengers interacting with each other along the route of a single PT line examined on a case study.

4.1 Significance of the research

Due to its advantages, multi-agent system (MAS) approaches (Uhrmacher & Weyns, 2009) are assuming growing importance in transportation modelling and simulation. This research has been conducted in accordance with the current scientific movement and tendencies, and aims to contribute to developing practices. Moreover, this case study specifically examines an operating PT
bus line. Therefore, the results obtained can be used by Auckland’s public authorities or the bus line’s operator. Insofar as the framework used for this case study is adaptable to other cases, it may be of interest to practitioners planning PT service in other cities throughout the world.

4.2 Scope and objectives of the research

To model part of Auckland’s PTN, commercial transport demand modelling and traffic simulation software products, such as VISUM (PTV AG, 2013b) and VISSIM (PTV AG, 2013a), were utilized. VISSIM made it possible to model and simulate the examined system as a MAS by playing different scenarios, which enabled predicting the effect of an expected change of transport demand on the PT supply as well as foreseeing the extent to which that supply should be increased so as to fulfil this demand.

The main objective of this study is therefore to provide practitioners with a simulation model enabling modelling parts of operating PTN by means of the MAS paradigm. In the process, five major tasks were undertaken:

(i) A literature review was conducted of recent articles concerning similar problems. It revealed the character of current research in the field, and the constraints and limitations confronting researchers;
(ii) In order to feed, calibrate and validate the simulation model, data were collected, processed, analysed and put into simulations;
(iii) The observed system was modeled as a MAS, and simulations were performed under different scenarios with the purpose of examining system performance measures;
(iv) The simulation output was analysed;
(v) Based on the analysis, reasonable conclusions were drawn.

4.3 Literature review

4.3.1 Public transit improvements

According to Farahani, Miandoabchi, Szeto, and Rashidi (2013), few researchers have been interested in the multimodal network design problem (MMNDP). This more complex problem encompasses different modes of transportation, such as cars and buses running during the same simulation. Several solution methods have been tested to determine bus routes and bus frequency – genetic algorithms (Gallo, Montella, & D’Acierno, 2011; Fan & Machemehl, 2006), heuristic methods (Lee & Vuchic, 2005; Cipriani, Petrelli, & Fusco, 2006) and tabu-search (Fan & Machemehl, 2008). Although these methods introduce the modal share concept (competition between PT and private cars), none of these works, except for Gallo, Montella, and D’Acierno
(2011) consider the interactions between the modes studied in the model. Modal share is a complex dynamic phenomenon reflecting an elastic PT demand and depending on many factors, such as travel time, value of time, PT vehicle capacity, comfort and others. This elasticity of transit demand is occasionally taken into account for PT design problem (Gallo, Montella, & D’Acierno, 2011; Fan & Machemehl, 2006; Lee & Vuchic, 2005), which allows for optimizing PT features under some transit demand changes of variable intensity in a more realistic manner. Regardless of the abundance of literature dealing with transit network design problem (TNDP), reportedly (Farahani, Miandoabchi, Szeto, & Rashidi, 2013) very little has been written about MMNDP. There has thus been little consideration for the impact of other modes on PTN performance. Although some researchers attempt to take into account the dynamic feature of PT demand (Gallo, Montella, & D’Acierno, 2011; Fan & Machemehl, 2006), the complexity of the TNDP tackled compels them to oversimplify some characteristics of PT system (unrealistic passenger behaviour, lack of interaction between cars and buses), which may be harmful to the precision of simulation output results. Rieser (2010) discloses that the main part of equation-based models dealing with research in multimodal and transit seem to have reached their limits because of the high complexity and high number of equations which constitute these models. To overcome these limits, one can use the multi-agent approach. Its general advantages (extensibility, fault tolerance and scalability) are described by Ceder (2007, 2016). MASs are indeed able to capture the autonomy, the collaboration and reactivity of thousands of agents evolving in a geographically distributed system and a dynamic environment. These agents – some individual entities – are able to communicate and interact with each other through their environment in order to achieve a particular goal. By nature, transportation systems, and thus PT systems, are well suited to the MAS approach (Chen & Cheng, 2010).

4.3.2 MAS and public transit

There are many public transit systems which have been modeled using the MAS paradigm for operational simulation (Balbo & Pinson, 2001; Zhao, Bukkapatnam, & Dessouky, 2003; Hadas & Ceder, 2008). A MAS for PTN management was proposed, specifically to monitor disturbances in PTN and detect inconsistent, instantaneously collected bus location data (Balbo & Pinson, 2001). Furthermore, another MAS has been created to coordinate bus-holding at several stops (Zhao, Bukkapatnam, & Dessouky, 2003). Hadas and Ceder (2008) created a MAS with the purpose of increasing the number of simultaneous transfers into a PTN, thereby increasing reliability and attractiveness of the latter.

Agent-based modeling and simulation (ABMS) theory has also been valuable to successfully evaluating urban transportation policies and strategies. There are studies in which passengers are considered as agents. In some cases, these papers only consider passengers’ socio-economic
characteristics, without focusing on the user’s decision-making process for route choice (Nguyen, Bouju, & Estraillier, 2012). When that user characteristic is effectively considered, passenger ability to learn from daily trips, and thereby modify daily travel plans from one day to another, is still ignored (Meignan, Simonin, & Koukam, 2007). To encompass this important learning dimension among passengers, Wahba and Shalaby (2006) presented an agent-based modeling (ABM) framework focused on passenger behaviour and decision-making in order to tackle the transit assignment problem. Their framework is, to some extent, similar to MATSim (multiagent transportation simulation) (Balmer, Rieser, Meister, Charypar, Lefebvre, & Nagel, 2009; Horni, Nagel, & Axhausen, 2016), because both frameworks consider PT users’ learning and decision-making process, which allows them to improve their daily travel plans successively, iteration by iteration, by taking into account the scores of their former daily plans.

Li, Zhang, Wang, Lu, and Mu (2011) proposed an artificial urban transit system (AUTS), based on the ABMS paradigm, to solve a network-optimization problem for a simplified transit network, such as the transit assignment problem, setting frequency and capacity of different transport modes, testing new route performance and relevance, or predicting the behaviour of the transportation system during a special event. This AUTS, run with AnyLogic software, also takes passengers’ day-to-day learning processes and decision-making processes into consideration. Contrary to MATSim, the latter processes are not based on a stochastic approach, but on consecutive, unacceptable daily travel time, not actually representative of passenger behaviour variability and sensibility (some passengers may change routes despite an acceptable score). This point was corrected by these authors in two subsequent works (Zhang G., Zhang H., Li, & Dai, 2014; Zhang & Li, 2014) concerning bi-level MAS. Nevertheless, the previous articles dealing with AUTS do not consider car traffic.

Kickhöfer, Kaddoura, Neumann, and Tirachini (2012), who considered the use of MATSim, after taking into consideration the impact of car traffic on modal share, showed the importance of passengers’ departure time decision for social welfare maximization (maximization of the sum of PT operator profit and user benefit) through optimal fares and headway. Their work was later improved by considering the randomness of the simulation, which represents users’ variable behaviour, car congestion and bus congestion related to passenger flows at bus stops (Kaddoura, Kickhöfer, Neumann, & Tirachini, 2015a; Kaddoura, Kickhöfer, Neumann, & Tirachini, 2012). In a subsequent paper, Kaddoura, Kickhöfer, Neumann, and Tirachini (2015b), using the same MAS aimed to optimize PT fares by introducing a marginal cost pricing approach. This optimization was achieved by enhancing MATSim. The significance of these four papers is diminished by their only considering a single multimodal corridor, without interaction between cars and buses (buses run on separate lanes).
Based on this review of the literature, three main conclusions can be drawn. First, in order that the simulation model be able to produce realistic and reliable results, in modelling a PT system as a MAS, other transport modes, such as private cars, taxis and bicycles should be considered. This is in contrast to some of the reviewed papers. Second, both MAS and ABMS are useful and well suited to modeling and simulating PTN in a relevant way. Some researchers have designed their own MAS to solve particular tasks (Balbo & Pinson, 2001; Zhao, Bukkapatnam, & Dessouky, 2003). Others, in order to deal with several problems related to PT, developed general MAS frameworks for PT system modelling and simulation (Rieser, 2010; Nguyen, Bouju, & Estraillier, 2012; Meignan, Simonin, & Koukam, 2007; Wahba & Shalaby, 2006; Li, Zhang, Wang, Lu, & Mu, 2011). There are also some researchers (Kickhöfer, Kaddoura, Neumann, & Tirachini, 2012; Kaddoura, Kickhöfer, Neumann, & Tirachini, 2015a) who use one of these frameworks to address their own objectives. Finally, in order to model an existing PTN or one of its routes, a suitable software product applying the ABMS approach, should be chosen to enable modeling of PT as a MAS and allowing for performing simulations and further exploring the system modeled.

4.4 Methodology

To model the PTN as a MAS, in particular a single route within the network, the ABM approach was chosen. This approach introduces the notion of an agent. An agent is an autonomous and intelligent entity, with its own characteristics and goals, able to take initiative and make choices. A MAS gathers several agents which are able to interact and cooperate with each other in order to achieve their respective goals. These agents evolve through an environment, setting the rules (such as physical laws) which compel their capabilities (Uhrmacher & Weyns, 2009). Moreover, the scalability feature of MAS allows for modeling thousands of agents in a manner comparatively easier than afforded by traditional simulation approaches.

VISSIM, the software for traffic, multimodal and transit microscopic simulations, was chosen to model PT as a MAS and perform simulations. Though VISSIM is based on discrete event (DE) simulation (Borshchev & Filippov, 2004; Smith, 1999) regarding the assignment process, one is able to strengthen the multi-agent feature of VISSIM by turning a DE-based process into a MAS concept. The main objective is to focus on the point of view of the entities, as opposed to the events by which they are processed and by which their state (Borshchev & Filippov, 2004) is changed. Although VISSIM is not a MAS platform, it is able to imitate multi-agent simulation of transportation systems. To some extent, its dynamic assignment process framework is similar to the MATSim’s demand optimization process framework. Its dynamic assignment process is an iterative process: car drivers can choose a route between an origin and a destination and modify the latter for the next iteration in order to increase the utility of their trip. The simulation ends when the travel
times and the traffic loads on the network are stable. Moreover, every vehicle does not choose the route supposed to generate the highest utility for the trip, but the travel demand between an origin–destination pair is distributed on all itineraries thanks to a Logit model (Ortuzar & Willumsen, 2001). Furthermore, one can model demand by trip chains. Therefore, the travel demand is discretized, and each vehicle has its own characteristic and its own goals. The latter can also be specified. Thus, via dynamic assignment process and trip chains, one can increase the MAS feature available in VISSIM by providing agents with the capability to learn and make choices regarding their itineraries.

4.5 Case study

The Agent-based modelling approach was applied to a case study focused on the route serving bus line number 277 in Auckland, New Zealand. The examined route runs from Britomart (B) in Auckland’s CBD to Waikowhai (W) in the suburb (Figure 4.1). The road network corresponding to the bus route and the main crossroads characterizing the road network were objects of modeling (to regulate the traffic). Thus, the agents implemented in the MAS interacting with each other are PT users, PT buses, car drivers and private cars.

4.5.1 Data collection, processing and analysis

Firstly, general PT-related data were collected as well as data regarding Auckland’s road network and vehicle traffic. The local public authority responsible for the management of PT in Auckland Region, Auckland Transport, provides Google with files containing data about Auckland’s PTN which is regularly updated and publicly accessible on their website (Auckland Transport, 2014c). Thus, the data concerning bus line 277, such as routes, bus stops (names and locations) and timetable were collected from these files. Traffic data along the route of bus line 277 (vehicle loads and vehicle type proportions at peak-hours) – these data were provided by Auckland Transport and dated from 2012 and 2013 (Auckland Transport, 2014d).

Secondly, in order to collect data at several levels, two different methods were applied on the spot. The first survey consisted of direct observations within buses enabling counting of passengers boarding/alighting the bus between the terminal stations. The vehicles operating along the observed bus line 277 were tri-axle single decker (rigid) buses equipped with two doors. Passengers were allowed to board the bus only through the front door and to alight through both the front and the rear doors.

The counts started on 21 July 2014 and ended on 8 August 2014, comprising the morning peak period between 7:30 A.M. and 9:30 A.M. for 15 working days. The method of direct observations facilitated determining the number of passengers using each bus stop and identifying bus loads (i.e.
passenger flows) along the whole route for both directions (34 sections) in direction B→W, 35 bus stops and 39 sections (i.e. 40 bus stops) in direction W→B. According to the timetable, the frequency in direction W→B (4 buses/h) is twice as high as the frequency in the opposite direction.

Due to the passenger counts and the timetable, it was possible to calculate the total hourly boarding volume for each stop and along each section for each day studied. Since information dealing with mobility behaviour and daily travel by Auckland citizens was not available, in order to run some simulations of scenarios likely to occur, and demonstrating the predictive power of the model developed, data from Auckland Transport’s transport program from 2012 through 2041 (Auckland Transport, 2014b) was used and some reasonable assumptions concerning the future levels of PT ridership have been made.
In order to adapt the supply side to the PT demand projected for the future, the day studied with highest passenger loads was considered (see Figure 4.2, showing passenger loads observed on July 24 and 31, and August 5).

It is obvious that for direction B→W the three curves follow a similar pattern. In direction (W→B) the three curves follow the same profile. The passenger load increases steadily and slowly until the sixteenth bus stop. Then, a large jump in the number of passengers on the bus is noticed, especially on August 5. Thereafter, from the 28th bus stop, a saturation level for the number of passengers between 65 and 70 was observed. From this saturation point, the bus was fully loaded, which suggests that the bus driver did not stop at stops, whether people wanting to board were waiting at these stops or not. Surprisingly, this range of values (65–70 passengers) does not match the real bus capacity, which according to Auckland Transport is 75 passengers. This means that on the average, in reality, 89% of the theoretical capacity is used. The difference between the theoretical and observed bus capacity results from the fact that standing passengers do not go to the far rear of the bus. Therefore, bus drivers see people next to them, and thereby consider the bus to be fully loaded, which is imprecise because in effect there is still space available at the rear of the bus. The saturation level lasts until the 36th bus stop. Then, the passenger volume on the bus decreases very quickly, probably because of the fact that the bus arrives at the CBD, containing many employment locations. According to the observed passenger flow patterns the highest passenger load on the bus occurred on 5 August 2014. This figure was used as an input parameter for running PT simulation runs so as to account for the maximum demand level.

(a) Days with highest passenger loads in direction Britomart → Waikowhai
Figure 4.2. Comparison of days with highest passenger loads in direction (a) Britomart→Waikowhai and (b) Waikowhai→Britomart

4.5.2 Modeling the MAS

4.5.2.1 Modeling road network

The information regarding Auckland’s road network used in the case study was processed within VISUM. The VISUM file was a set of nodes and links corresponding to a simplification of real road sections and intersection points. Given that the road network file contained a satellite photograph of Auckland Region, it was possible to superimpose that photo with the set of nodes and links. In parallel, Google Maps (2015) which was used to represent the bus line marked out all 74 bus stops. The satellite pictures on both Google Maps and VISUM, made it possible to add each bus stop on the virtual road network was at its exact location. Once the bus stops were linked by creating the bus route, the VISUM file was imported in VISSIM as a road network containing each bus stop corresponding to the bus line route. Nonetheless, some modifications on the VISSIM road network were performed so as to create a more realistic model: (i) given that the imported network in VISSIM was composed of roads containing one lane per direction, the capacity of some main roads had to be increased by doubling the number of lanes, thus doubling the road capacity; (ii) In order to model the buses dedicated area at bus stops, blocks were created on the side of the road at each bus stop location, so that buses not interfere with cars while passengers are boarding and/or alighting; (iii) Taking into account that most private vehicles do not follow the whole bus route, exits (corresponding to the main intersections) for these vehicles were created enabling them to leave the simulation. Thus, the proportion of vehicles leaving the simulation was chosen, making it possible to regulate vehicle traffic along the route.
4.5.2.2 Modeling agents

The agents interacting with each other in the modeled MAS, shown in Fig. 4.3, were as follows:

- **Private vehicles** generated on several locations along the road network resulting from volumes extracted from traffic counts (Auckland Transport, 2014d). Thus, some cars appear and merge into the traffic flow directly from specific links according to the volume specified.

- **Private vehicle drivers** have their own driving behavior. For example, they react to the behavior of close vehicles and can demonstrate several behaviors when approaching an intersection. As data regarding Auckland car divers was not available, the default setting for the simulations was chosen.

- **Buses**: The capacity of buses running along bus line 277 was collected on the spot. Furthermore, both departure times from Britomart and Waikowai were implemented. Bus frequency is not the same for both directions: during the morning peak period in direction B→W the headway is 30 min (i.e. bus frequency is 2 buses/h), whereas in direction W→B, on the average, one bus departs every 15 min (i.e. the frequency is four buses/h).

- **Bus driver** behaviour was also modeled by using the built-in VISSIM functionality, e.g. if the bus is full, drivers may decide to skip bus stops regardless of whether or not passengers are waiting for the bus at these stops.

- **Public transit users** (PT demand) were modeled at bus stops. These passengers generate dwell time at bus stops when they board/alight the bus. Therefore, if the number of passengers is high, the bus may incur some delay. Boarding and alighting times in the simulation model were calculated as an average of the values stored in tables (Liu, Deng, & Yi, 2011).

![Figure 4.3. Interactions between the agents in the MAS](image)

**Figure 4.3. Interactions between the agents in the MAS**

modeled. 1. Private vehicles may cause a delay for buses due to a congestion, which would incur an increase of dwell times at bus stops. 2. By boarding and alighting, PT users may delay buses. The larger the number of passengers, the bigger dwell time is. On the other hand, buses delay may lead to an increased dwell time at stops. 3. Obviously, bus drivers drive buses, and his/her behaviour may affect the other vehicles on the road. 4. Behaviour of car drivers may also affect other vehicles running along the road network. 5. Private vehicles and buses interact with each other on the road network. An overwhelming number of cars may create congestion, and therefore may delay buses. 6. Private vehicles drivers’ behaviour interacts in several ways with buses. 7. Bus driver may skip bus stops if the bus is full, which may indirectly increase the dwell time.
4.5.2.3 Key input parameters and output variables used in the modeling

Inasmuch as VISSIM is software which takes many features of traffic into account, many variables are considered, and many calculations are performed during a simulation. However, there are some key variables and parameters of particular interest for this case study.

The assumptions made regarding the PT demand, passenger mode choice, path choice and boarding choice (especially in crowded buses) are based on the following reasons:

- The PT demand in the simulation model was modelled at bus stops. It is based on the boarding volume (number of passengers boarding the vehicle) obtained as a result of direct observations within buses running along the route of the studied PT bus line number 277 for the day with highest demand (bus load) during morning peak hour;
- Based on the above, the simulation model is fed with boarding volumes representing passengers who have chosen to make trips with bus transport as a mode (in particular bus line 277);
- The model’s logic is such that buses follow a predefined route of a real PT line constituted by the sequence of bus stops and their location. A hypothetical simulation scenario providing passengers with an alternative bus route serving the same or another PT line has not been considered;
- When buses are fully loaded, drivers may decide not to stop at bus stations regardless of whether there may be passengers waiting to board the bus. This means that these passengers will wait to board the next bus, which in turn would increase their waiting time (although they would be able to wait less either by getting on buses serving another PT line going through the same stops or just choosing alternative mode of transport – features that the model does not consider). The combined effect of an increased bus frequency and vehicle capacity in the simulation scenarios has led to a decreased average passengers’ waiting times at bus stops.

Table 4.1 summarises the main parameters used as an input to the model, the accompanying assumptions made when necessary and their provenance. The input and output parameters of the simulation model are illustrated on the scheme on Fig. 4.4.

After simulations had been run, the output results were collected, processed and analysed. The output variables of interest in this case study were passenger load, bus travel time and dwell time.
Table 4.1. Input parameters.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Measuring unit</th>
<th>Assumption</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus frequency</td>
<td>Buses per hour</td>
<td>-</td>
<td>Auckland Transport</td>
</tr>
<tr>
<td>Bus capacity</td>
<td>Passengers</td>
<td>-</td>
<td>Auckland Transport</td>
</tr>
<tr>
<td>Boarding volume</td>
<td>Passengers per hour per stop</td>
<td>The boarding volumes used to feed the simulation come from the number of passengers boarding at each bus stop on August 5, 2014 – the day with the highest travel demand during the morning peak period</td>
<td>Survey on buses and Auckland Transport (timetable)</td>
</tr>
<tr>
<td>Traffic volume</td>
<td>Vehicles per hour</td>
<td>As there were no traffic count data for some of the road sections served by buses, a known traffic volume data along close (in terms of capacity) road sections has been assigned to them</td>
<td>Auckland transport</td>
</tr>
<tr>
<td>Boarding and alighting times</td>
<td>Seconds per passenger</td>
<td>The time for boarding and alighting used in the simulation model was calculated as an average of the values stored in tables (Liu, Deng, &amp; Yi, 2011)</td>
<td>Liu, Deng, and Yi (2011)</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>km/h</td>
<td>In order to reflect the specifics of the real road and traffic conditions, a maximum speed up to 58 km/h was assigned to cars and 50 km/h to buses</td>
<td>-</td>
</tr>
</tbody>
</table>

4.5.3 Simulation model – calibration and validation

4.5.3.1 Current state of the modeled system

The calibration of the model, instead of applying search methods and estimating a computational performance, was done by adjusting parameters until the model output results were as close as possible to the modelled real-life system. The calibration process was carried out by using a reference scenario representing the actual state of the examined system.
The calibration parameters used are as follows:

- Traffic volume (vehicular car traffic) running along the sections of the road network;
- The PT demand is modeled as number of passengers boarding the vehicle at bus stops in the day with highest demand during the morning peak period;
- Boarding and alighting times;
- Vehicle speed;
- Duration of the simulation.

The validation of the model was done through a comparison of the simulation output results with data collected from direct observations in buses going along the route of a PT line carried out on 5th of August 2014 on a case study in Auckland, New Zealand.

The data used for validation purposes includes the following validation parameters:

- Passenger loads along the route in the bus departing from the terminal station (Britomart) at 7.30am;
- Departure and arrival times for the same bus.

To validate the model, a linear regression analysis as a Goodness-Of-Fit test of the actual (observed) versus simulated loads was performed. The evaluated coefficient of determination (Davis & Pecar, 2013), $R^2$, having value close to 1, shows that the model satisfactorily reflects the observed system.

It is known (Davis & Pecar, 2013) that the true relationship between the independent variable $X$ and the dependent variable $Y$ for the whole population ($Y = \beta_0 + \beta_1 X$) is estimated from the sample relationship $\hat{y} = b_0 + b_1 x$. In order to identify if the relationship between $X$ and $Y$, modelled by linear regression equations, is statistically significant, it was necessary to identify if the slope $\beta_1$ was significantly different from zero. In this regard, in addition to the coefficient of determination ($R^2$-Square) used as a measure for the model’s validation, t-tests for statistical significance of the slope (Kirkup, 2002; Davis & Pecar, 2013; Schmuller, 2016) were performed for each of the derived linear regression equations of the type $\hat{y} = b_0 + b_1 x$.

To check the statistical significance of the slope $\beta_1$, the following two hypotheses were raised and checked:

- Null hypothesis, $H_0$: The slope of the regression line is equal to 0, i.e. $\beta_1 = 0$;
- Alternative hypothesis, $H_1$: The slope of the regression line is not equal to 0, i.e. $\beta_1 \neq 0$. 

70
The value $t$ of the $t$ statistics was calculated by using formulae (4.1) below:

$$ t = \frac{b_1 - \beta_1}{s_{b1}}, $$

(4.1)

where:

$b_1$ – regression coefficient (slope) whose value was calculated from (4.3):

$$ b_1 = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{N}(x_i - \bar{x})^2}, $$

(4.3)

where:

$N$ – number of observations;

$x_i$ – $i^{th}$ value of the independent variable $x$;

$y_i$ – $i^{th}$ value of the dependent variable $y$;

$\bar{x}$ – average value for the sample of $x$ values calculated as

$$ \bar{x} = \frac{\sum_{i=1}^{N}x_i}{N}, $$

(4.4)

$\bar{y}$ – average value for the sample of $y$ values computed as:

$$ \bar{y} = \frac{\sum_{i=1}^{N}y_i}{N}, $$

(4.5)

$\bar{x}$ and $\bar{y}$ were used in (4.6) to evaluate the other regression coefficient $b_0$ (the intercept):

$$ b_0 = \bar{y} - b_1.\bar{x}, $$

(4.6)

$s_{b1}$ - standard error of the slope evaluated through the equation:

$$ s_{b1} = \frac{s_{yx}}{s_{xy}(N-1)} $$

(4.7)

in which:

$s_{yx}$ – the standard error of the estimate was computed with the following formulae:

$$ s_{yx} = \sqrt{S_{yx}^2} = \sqrt{\frac{\sum_{i=1}^{N}(y_i - \bar{y})^2}{N-2}}, $$

(4.8)

where:

$S_{yx}^2$ – residual variance;

$\hat{y}_i$ – $i^{th}$ predicted value of the dependent variable $y$, calculated after substituting the $i^{th}$ value of $x$ in the regression equation

$$ \hat{y}_i = b_0 + b_1.x_i $$

(4.9)
and

\[ S_x - \text{standard deviation of a sample for the } x \text{ variable was calculated as} \]

\[ S_x = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \] (4.10)

By substituting the \( x \) (collected passenger loads) and \( y \) (simulated passenger loads) values (for direction Britomart – Waikowhai, B→W) in the above formulas, the following values of the examined parameters were calculated:

\[ N = 34; \]
\[ \bar{x} = 9.382 \text{ and } \bar{y} = 9.118; \]
\[ b_1 = 0.857 \text{ and } b_0 = 1.073; \]
\[ S_x = 9.297; \]
\[ S_{yx} = 0.52; \]
\[ S_{b_1} = 0.0097. \]

For \( \beta_1 = 0 \) (Kirkup, 2002; Davis & Pecar, 2013) formula (4.1) for the \( t \) statistics simplifies to:

\[ t = \frac{b_1}{S_{b_1}}, \] (4.11)

After the calculated values of \( b_1 \) and \( S_{b_1} \) were substituted in (4.11), for the test statistics \( t \) was obtained value equal to:

\[ t = \frac{b_1}{S_{b_1}} = \frac{0.857}{0.0097} = 88.012. \]

The criterion based on which a decision was made regarding the statistical significance of the slope was a comparison of the calculated \( t \) statistics with the critical value \( t_{crit} \) for the \( t \) distribution. If \( |t| > t_{crit} \), we can reject the null hypothesis \( H_0 \), which would mean that the slope is statistically different from 0 (Kirkup, 2002).

For the \( t \) distribution two-tailed \( t \)-test, accepted level of significance \( \alpha = 0.05 \) and degrees of freedom (Davis & Pecar, 2013) \( df = N - 2 = 34 - 2 = 32 \), the corresponding critical value \( t_{crit} \) obtained from the table for critical values of the \( t \)-distribution\(^{17} \) was \( t_{crit} = 2.037 \) which exactly matches with the value returned by the T.INV.2T(\( \alpha \),\( df \)) Microsoft® Excel function with arguments significance level \( \alpha \) and degrees of freedom \( df \).

\(^{17}\)https://www.medcalc.org/manual/t-distribution.php
Since $|t| = 88.012 > 2.037 = t_{crit}$, the null hypothesis $H_0$ was rejected, therefore the alternative hypothesis $H_1$ was accepted. This means that the slope of the regression line significantly differs from 0, i.e. it is statistically significant. Alternatively, the two-tailed p-value in Microsoft® Excel’s Data Analysis (Regression) could be used for checking the statistical significance of the slope. In this specific case $p-value = 9.44591E-40 < 0.05 = \alpha$ which means that we can reject the null hypothesis and accept the alternative (as in the above comparison of both the t values – the calculated t statistics and the critical $t_{crit}$ value taken from tables for the t-distribution).

The same test for statistical significance of the slope was performed for direction Waikowhai – Britomart (W→B) by substituting the x values (collected passenger loads) and y values (simulated passenger loads) for accepted level of significance $\alpha = 0.05$ and calculated degrees of freedom equal to $df = N – 2 = 39 – 2 = 37$.

And since again $|t| = 25.174 > 2.026 = t_{crit}$, the null hypothesis $H_0$ was rejected, i.e. the alternative hypothesis $H_1$ was accepted stating that the slope of the regression line is not equal to 0.

The above values calculated by using formulas (4.1 – 4.11) matched the values of all the parameters obtained after the “Regression” functionality of the “Data Analysis” tool in Microsoft® Excel was used (Appendix B, Tables B.1-B.6) with the same data input, which validated the accuracy of the obtained results and decisions made during the performed test for statistical significance of the slope.

4.5.3.2 A prospective scenario

Once the calibration and validation stage were done, it was possible to examine and analyse scenarios played using the simulation model. A prospective scenario has been created, the purpose of which was to reproduce the future state of the examined system in 2024. In this regard, prospective data related to Auckland Region’s transport system future state was used, and

![Figure 4.5. Linear regression in directions B→W (a) and W→B (b). (a) Actual vs. simulated passenger loads in direction B→W; (b) actual vs. simulated passenger loads in direction W→B.](image)
particularly the likely future car volumes on the road network and the expected increase of PT trips. Assuming that the data evolution follows linear trend, the following proportions for the forecasted year have been calculated:

- A 17% augmentation of the number of private vehicle trips assimilated as an increase of the volume of private vehicles.
- A 31% augmentation of the number of PT trips assimilated as an increase of the number of boarding passengers.

After having observed and analysed the whole picture during the simulation for the prospective scenario, in order to satisfy the prospective demand along bus line 277 during the morning peak, 12 scenarios, including a combination of 3 different capacities and 4 pairs of frequencies (one for each direction) have been played (Table 4.2). The indicator measuring the effectiveness of the capacity/frequency pairs was average passenger waiting time at bus stops.

**Table 4.2. Experimental capacities and frequencies.**

<table>
<thead>
<tr>
<th></th>
<th>British – Waikowhai</th>
<th>Waikowhai – British</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>871</td>
<td>805</td>
</tr>
<tr>
<td>3</td>
<td>627</td>
<td>516</td>
</tr>
<tr>
<td>4</td>
<td>516</td>
<td>408</td>
</tr>
<tr>
<td>5</td>
<td>408</td>
<td>311</td>
</tr>
<tr>
<td>4a</td>
<td>980</td>
<td>805</td>
</tr>
<tr>
<td>5</td>
<td>805</td>
<td>722</td>
</tr>
<tr>
<td>6</td>
<td>722</td>
<td>685</td>
</tr>
<tr>
<td>8</td>
<td>85</td>
<td>238</td>
</tr>
<tr>
<td>70a</td>
<td>832</td>
<td>500</td>
</tr>
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<td>85</td>
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<td>417</td>
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<td>100</td>
<td>835</td>
<td>499</td>
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<tr>
<td>500</td>
<td>499</td>
<td>411</td>
</tr>
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<td>987</td>
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<td>1211</td>
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<td>897</td>
<td>1211</td>
<td>1133</td>
</tr>
<tr>
<td>747</td>
<td>1133</td>
<td>973</td>
</tr>
<tr>
<td>727</td>
<td>973</td>
<td>677</td>
</tr>
</tbody>
</table>

*aCurrent vehicle capacity/frequency.*

The simulation output results obtained based on the scenarios played considering different combinations of bus capacities and frequencies are shown in Figure 4.6(a–d) representing a comparison between simulated and actual load profiles for the current and prospective year:

It is noteworthy that the time difference between actual and simulated arrival times for the bus departing from Britomart at 7:30 A.M. is only 7 min (08:08AM for the actual arrival time vs. 08:15 AM for the simulated), and 4 min in the opposite direction (09:19AM vs. 09:15AM, respectively).
(a) Actual vs. simulated passenger loads in direction B→W in 2014

(b) Actual vs. simulated passenger loads in direction B→W in 2024

Figure 4.6. Comparison of actual vs. simulated passenger loads in 2014 and 2024 in direction B→W (a, b) and W→B (c, d), respectively.
As expected, the projected number of passengers on the bus in 2024 is higher than at the present. It appears that for the direction B→W (Figure 4.6(a,b)) both curves follow the same profile. It is also interesting to observe here that despite the higher PT demand the bus is not utilized at its full capacity.
Concerning the opposite direction (W→B), both curves have quite similar profiles, again with expected demand for 2024 greater than the actual. However, at the first stops, there are no passengers traveling on the bus (due to a bus delay caused by higher traffic volume, passengers may have boarded the previous bus). Indeed, according to the simulation output results, the studied bus arrived at 8:31 A.M. at Waikowhai and at 9:41 A.M. at Britomart, which compared to 2014 is 23 and 22 min more, respectively.

Experimenting with 12 scenario values for the capacity/frequency pairs resulted in two types of graphs (Figure 4.7(a–d)). The first type compares the average PT passenger waiting time at bus stops for constant frequencies and changeable bus capacity, whereas the second type compares the average passenger waiting time at bus stops for constant capacity but changeable frequencies. Regarding the first type of graphs, as expected, it is evident that regardless of the direction, the higher the frequency, the lower the waiting time at bus stops. Depending on bus direction, there are two different behaviours:

(a) Average passenger waiting time in function of changeable bus capacity and constant bus frequency in direction B→W

(b) Average passenger waiting time in function of changeable bus capacity and constant bus frequency in direction W→B
For buses heading for the Auckland’s suburb (Figure 4.7(a)), it seems that the capacity has no impact on the average waiting time at bus stops, which is probably due to the fact the bus is not utilized to its full capacity (in contrast to Figure 4.7(b));

In the opposite direction (Figure 4.7(b)), it was observed that for low and medium frequencies, the higher the capacity, the higher the PT users’ waiting time at bus stops. It could have been expected that a high capacity reduces the average waiting time, because more passengers are able to board the bus. This could be due to the fact that the total boarding and alighting time is higher when the bus capacity is greater and when the demand is high enough to use the whole bus capacity (see Figure 4.7(d)). Therefore, the bus may remain longer at the bus stop where the demand is particularly high, which generates longer waiting times at subsequent stops. Given that
the frequency is too low, people waiting at the other bus stops have no choice but to wait for that bus, which increases the total waiting time at bus stops. The observed effect is probably reinforced by the congestion caused by the traffic which is high during morning peak-hours in this direction to CBD, which as a result reduces bus speed. Regarding the highest frequency (Frequency 3), changes in bus capacity do not seem to affect the average waiting time. This probably means that the frequency cancels both of the negative effects (i.e. a high boarding and alighting time combined with high congestion levels). Due to buses serving these stops regularly, there is no time for the PT demand at bus stops to increase.

In summary, high bus frequencies lead to a reduction of passengers waiting time at bus stops. On the contrary, when the demand at stops is high and the number of departures per hour is not consequent, the high bus capacity leads to an augmentation of the average waiting time at bus stops.

As for the second type of graph, it can be observed that, as previously, high frequencies lead to a decrease of passenger waiting time at bus stops. The same conclusions were drawn here as for the first type of graph: when the PT demand is not high enough to match bus capacity, this capacity has no effect on the average waiting time at bus stops (Figure 4.7(c)). In case the demand is high and such is the case for traffic congestion, the high capacities considered (due to the larger number of passengers boarding the bus) are the source of increased passenger waiting times at bus stops, unless the frequency is increased (Figure 4.7(d): when the frequency of service is eight buses/hour, the average waiting time is the same, regardless of the capacity). Thus, in order to satisfy the expected PT demand in 2024 on bus line 277, one should take the highest frequency acceptable for the transit company, in case the demand is insufficient to match the capacity of small buses. Nevertheless, when the demand transcends the bus capacity on a particular section of a considered bus line (Figure 4.6(d)), and when the congestion is high on that section, it seems inappropriate to increase bus capacity: it would only increase passenger waiting time at stops. Thus, transit operators may consider increasing bus frequencies of the examined bus line as an option instead of operating buses with greater capacity.

4.6 Conclusions

In this chapter a simulation model of a real-life bus route running within Auckland’s PTN has been developed. The simulation model enabled modelling the interaction of buses, passengers, and cars along a single route as a small-size MAS and performing simulations under scenarios considering anticipated PT demand on the observed bus line.

The proposed simulation model calibrated and validated for Auckland’s PT bus line provides a helpful tool enabling modelers and planners to perform simulations by which the modeled system can be observed, its performance measures analysed, and reasonable operational decisions made.
The simulation output results have demonstrated that when PT demand is less than bus capacity, that capacity does not affect the average waiting time at bus stops. In cases where PT demand is high, not surprisingly, the high bus capacity, resulting in an increased number of passengers boarding the bus, indirectly causes increased passenger waiting times, unless the frequency of service is increased. These results can serve PT operators well in the trade-off situation when choosing between increased bus frequencies and larger size bus capacities, especially when the PT demand at bus stops is high. Given that the focus in the study lies on PT users, both the results obtained in the case study and the proposed simulation model could serve as a basis for further research that would take PT users’ interests and reliability of the PT service into consideration. That would be a research aimed at examining the impact of an increased frequency of service on passenger waiting times which in turn impacts the total passenger travel time on the one hand and, on the other hand, establishes to what extent increased vehicle frequency would contribute to better utilisation of the unused vehicle passenger capacity. The above intent was realised in a study which is the subject of the next chapter.
CHAPTER 5. MODELING AND SIMULATION OF HIGH-FREQUENCY AUTONOMOUS PUBLIC-TRANSPORT SERVICE

This chapter is derived in part from an article published in International Scientific Journal "Mathematical Modeling" in 2018, available online: http://stumejournals.com/journals/mm/2018/2/73.

One of the most significant factors influencing people’s lives nowadays is time. When doing their daily activities, such as going to work, school, or shopping, people aim to save time, especially when travelling in private cars or on PT. Therefore, to make PT more competitive, public operators and authorities should fulfil transport demand (Ceder, 2007, 2016; Vuchic, 2005) by providing passengers with adequate transport supply (Ortuzar & Willumsen, 2001) and reliable and regular transport service. This can be done either by running large-capacity vehicles along a particular PT route or small-size vehicles with increased frequency (reduced headways), which reduces the uncertainty and waiting times, thus resulting in PT service with greater punctuality.

A small number of large-size vehicles running with lower frequency is less expensive for the carrier in terms of operating costs but leads to increased waiting times for passengers at PT stops (stations). On the other hand, more frequent public transport service decreases passenger waiting times at PT stations along the route, but requires more vehicles and drivers, thus leading to increased operating costs, including wages to drivers, as well as to increased vehicular traffic and CO₂ emissions.

In some towns around the world¹⁸, PT is offered free to riders along some routes. Therefore, regardless of the kilometres travelled by the vehicles and without taking into account their operating cost and the cost of driver wages, the question that needs to be answered in this case is: Which PT control strategy would provide the adequate PT supply (with reduced waiting times at stops) to address the PT demand, by serving as many passengers as possible, regardless of the cost to the operator? The main priority, therefore, is the level of service and reliability. One of the possible and modern ways to achieve this is to implement a PT service operating autonomous vehicles capable of providing riders with increased reliability and enough flexibility to accommodate the fluctuations of PT passenger demand along the different routes throughout the hours of the day.

The simulation model presented in Chapter 4 modelled part of a real-life PTN as a small-scale multi-agent system modelling the interaction between the agents, buses, passengers, and cars on a bus route as a case study in Auckland (New Zealand). Unfortunately, in its current state the model is only applicable to the examined bus route, which is characterised with specific route parameters (number of stops and section lengths), vehicle parameters (capacity and travel speed), operational

parameters (vehicle frequency), and of course passenger demand at bus stops as observed during morning peak hours. That led to the need to develop the more flexible and customisable simulation model presented in this chapter. Chapter 5 continues the topic of chapter 4 considering simulation of the passenger transportation process along a route of a single PT line and adds a value through the application, on a numerical example, of the developed discrete-event simulation model implementing the concept of autonomous cars in modelling and simulation of a high-frequency, metro-like PT service provided by vehicles running on isolated (exclusive) lanes assumed to be driverless.

5.1 Objective and tasks

The main objective of the study presented in this chapter was to improve the reliability of PT service by reducing the average waiting time experienced by passengers. As part of the study, the following tasks were employed:

(i) conducting a literature review of articles discussing models and tools related to the problem examined;
(ii) developing a simulation model enabling the modelling of passengers’ transit process (PTP);
(iii) application a numerical example calibrated using different simulation scenarios;
(iv) analysing and discussing the simulation output results; and
(v) drawing reasonable conclusions and outlining further research work.

5.2 Scope of work

The scope of work was to accurately model a single line of a PT service and precisely simulate the PTP. This was attained by examining a variety of simulation modelling systems, simulation programming languages, and simulation tools.

5.3 Significance of work

This work resulted in a flexible simulation model developed using the novel concept of autonomous vehicles. This concept was applied to the PT field through the example of an assumed autonomous-bus service. The outcome of the example is metro-like, high-frequency (short headways), punctual autonomous buses running on isolated lanes (no intersections, no traffic lights, and no congestion) and arriving at bus stops on time.

5.4 Literature review

Reliability of public-transit service, a main factor that can make PT more attractive to users and thus encourage them to choose PT as a preferred transport mode, is very difficult to achieve and preserve nowadays due to the negative impact of a large number of factors, such as traffic, shared
lanes, inefficiently planned PT service, and so on. Thus, PT planners need to seek solutions that provide PT users with a reliable and flexible enough PT service that is capable of satisfying passenger demand and responding to fluctuations in demand.

Polus (1978), who created a model for predicting reliability, defined transit-service reliability as “the ability of the service to provide a consistent service over a period of time”. For the purpose of reliability analysis Polus defined the measure of reliability along a bus route as “the inverse of the amount of variability of the performance measure from day to day”. Along with travel time, bus headway, and adherence to the schedule, one of the measures of performance is waiting time at bus stops.

According to Silcock, cited in (Ceder, 2007), one of the measures of service reliability mentioned is the average waiting time of passengers. Additional measures are: the number of buses taking x minutes longer than scheduled; the percentage of buses that depart between one minute early and four minutes late; passengers’ excess waiting time; and the difference between the actual average waiting time and the calculated waiting time.

Vuchic (2005), who outlined the steps for achieving increased reliability of transit services, suggests estimating the value of increased reliability of transit services through the results it brings (some of which are quantifiable, while others are qualitative) and the impact on the affected parties: users, that is, passengers (experiencing decreased waiting time), operators (experiencing reduced delays, evenly loaded vehicles and fewer vehicle-kilometres, and reduced operating costs due to a reduced number of vehicle drivers), and the city (reduced street congestion and improved attitudes towards PT).

Ceder (2007, 2016) classified the attributes and measures of reliability of transit service. Ceder focused on examining those attributes that are of concern to both passengers and transport. With regard to reliability, the main attributes of concern to passengers are: waiting time, boarding time, seats available, alighting time, travel time, and so on. Some of the main sources of unreliable service mentioned by Ceder are: short spacing between stops, uneven loads, overloaded vehicles, and lack of vehicles available for service. One of the techniques proposed by Ceder (regarding improved planning and scheduling) to resolve reliability problems is increased service frequency.

Another useful technique, which helps to improve service reliability, is granting PT vehicles priority by means of exclusive lanes (Ceder, 2007) also known as priority lanes. Influenced by the Braess Paradox and aimed to increase the attractiveness of the PT system and improve traffic circulation, Bagloee, Sarvi, and Ceder (2017) mathematically defined the transit priority lane design problem as a bi-level, mixed integer, nonlinear programming task which they applied in solving a numerical example using real-life data for the transport network at Winnipeg, Canada, with the
purpose of identifying, through a merit index calculated, the best subset of candidate links that can be considered potential PT priority lanes.

Based on the above review, one of the ways to improve transit service reliability is, on the one hand, to decrease one of its measures – average passenger waiting time at stops/stations – by increasing service frequency of autonomous (driverless) vehicles running along the route (which would cut costs for wages) and, on the other hand, by providing exclusive (separated) lanes that would reduce to a minimum the headway's deviation, thus avoiding the impact of delays on travel times between stops incurred on signalised intersections and along the road due to traffic congestion.

Since PT performance measures, such as headways, passenger waiting and travel times, and passenger inter-arrival times at stops, vary over time, they can be considered random variables characterised with statistical characteristics, such as mean (average) value, standard deviation, and coefficient of variation (Kirkup, 2002), which can be used to satisfactorily measure the reliability of transit service under uncertainty. Therefore, in this chapter the best scenario, among the various scenarios considered is the one that results in the lowest average passenger waiting time at bus stops and/or least number of unserved passengers waiting to be transported. Consequently, there is a need to develop a model that can be easily implemented on a PT line route and that will improve the reliability of the transit service provided.

As a result of research work in the field of PT, a large number of bus-line models have emerged and been documented in the literature over the years, such as mathematical models (Andersson & Scalia-Tomba, 1981; Codina, Marín, & López, 2013), mesoscopic simulation models (Bauer, 2013; Bauer, 2014; Cats, Burghout, Toledo, & Koutsopoulos, 2010), and microscopic simulation models (Gunawan F. & Gunawan A., 2014; Dimitrov, Ceder, Chowdhury, & Monot, 2017) that have been developed with computer programming and simulation languages, specialised or general-purpose simulation software systems, or within the working environment of simulation frameworks (Dessouky & Leachman, 1995).

Some of the models have been used to solve numerical examples, others have been applied to real-world case studies to analytically describe and model the passenger transportation process along bus or railway lines, and others still to simulate the systems modelled and further examine their performance.

Andersson and Scalia-Tomba (Andersson & Scalia-Tomba, 1981) proposed a mathematical description of a complex model of an urban bus route developed and used by Andersson, Hermansson, Tengvald, and Scalia-Tomba (1979) with the purpose of evaluating and applying control strategies aimed at reducing the irregularities and delays in the bus service. The concept of a bus route is applied as parallel-running sub-routes called “service variants” by the authors. Along
with the great level of detail and realism that the large and complex model provides, which can be considered an advantage, there are two main problems that need to be mentioned as disadvantages:

(i) the bigger the model, the larger the amount of data required to feed it and the bigger the requirement for data accuracy (which incurs more costs and involves more technical data-entry and processing work);

(ii) the more complex the model, the higher the computation requirements for software tools, which sometimes impose some limitations. The level of detail the model provides (due to its complexity) may be retained or reduced by dropping some details. As the simulation model is intended for planning and evaluating control strategies with the presented data, neither Poisson passenger arrivals nor simplified travelling assumptions can be tested with the model.

Dessouky and Leachman (1995) proposed a computer simulation modelling methodology used to develop (using SLAM II) simulation models that have been applied to a case study to examine and analyse the capacity of single- and double-track rail networks and evaluate the train delays for the two proposed network configurations (alternatives) for rail traffic forecasts. The main advantage of the model is that it does not depend on the network's size and it is insensitive to the configuration of the tracks. Its main disadvantage is that the accuracy is dependent on how the rail network is composed of track segments and junction resources on which two or more rail lines merge.

Cats, Burghout, Toledo, and Koutsopoulos (2010) presented a simulation model developed within an object-oriented, event-based mesoscopic simulator called Mezzo applied to a high-demand real-life PT bus line in Tel Aviv (Israel) with 30 stops in the inbound direction and 33 in the outbound during peak hour, examined under different simulation scenarios using passenger arrivals following Poisson distribution. It is demonstrated that the simulation data replicates the observed data.

The main advantages of the transit line simulation model are that:

(i) the model can reproduce the “bus bunching” phenomenon;

(ii) the model captures the propagation of delays through the system and from trip to trip;

(iii) the simulation output results include stop-level statistics, such as early and late arrivals, dwell times, number of boarding and alighting passengers, bus loads, and travel times between stops. At the same time, aggregations at the level of the trip, the vehicle, or the line, such as schedule adherence, headway and passenger wait-time distributions, load profiles, and other level of service measures, are also evaluated and computed.

In order to plan PT service by setting the bus frequency on a set of auxiliary bus lines bridging a set of disrupted stations of a rapid transit or metro system, Codina, Marín, and López (2013) developed a mixed-integer, non-linear mathematical programming model that has been applied under different levels of demand for two real case studies: a railway corridor in Madrid with four
rail stations and a bus bridging system for a segment of a metro line in Barcelona composed of ten metro stations.

The advantage of the model presented is twofold:

(i) The model takes into account the main factors involved in the congestion of transit lines using an analysis that can be extrapolated with small adaptations to situations other than bus bridging systems;

(ii) The model enables the detection of bottlenecks along selected lines (which bus stops operate at the maximum number of bus services, the maximum number of buses able to queue at a bus stop, and the maximum number of passengers who can be accommodated waiting at the bus stop).

As a basic output, the model provides the number of buses assigned to each bus line as well as bus operating frequencies.

The disadvantages of the model are that (i) it is static, as it takes into account the average flows of passengers over a given period of time (e.g., during morning “peak” hours), and (ii) finding a feasible solution requires a large number of input parameters and high-performance computation software such as CPLEX19.

Bauer (2014) built a stochastic simulation model of a bus line that was applied to a numerical example considering an artificial bus line that consists of eight stops (seven sections) in each direction. Three variants considering different types of sections were examined: variant 0 (on each rote section buses use common lanes shared with the other vehicles), variant 1 (separated lanes along the entire lengths of the route sections), and variant 2 (partially separated lanes, i.e., combination of variant 0 and variant 1). The structure of the model is based on graph theory – each of the model's elements of any bus line are represented as a simple digraph structure in which the set of vertexes are bus stops along the line and the set of edges are the segments between the bus stops. The model is described by Bauer in greater detail in (Bauer, 2013), in which the model was verified by comparing the simulation output results for two urban lines with the results of independent observations, and subsequently the model was put into practice on a sample bus line in Cracow, Poland.

Mathematically, the proposed model of a bus line operation was created as a matrix system of discrete events expressed by matrix equations.

The numerical realization of the model was done using “AUTOBUS” software, which was created by the author using the built-in programming language in Mathematica 6.0.

The stochastic simulation model, which the author claims fills the gap between the micro- and macro-simulation models, has the following advantages:

(i) the model could be applied in a network analysis when estimating input data for macrosimulation models of public transport networks as well as the tool for better network calibration;

(ii) another possible application of the model is as a scheduling procedure, especially when a new line is added, before starting and during the first phase of operation;

(iii) the model has an open structure, which allows additional elements to be added in it in future.

The model proposed has not been applied to different vehicle types (capacities) running with different bus frequencies.

Gunawan F. and Gunawan A. (2014) developed a simplified microscopic discrete-event bus rapid transit (BRT) simulation model using Matlab SimEvents. The application of the model on a numerical example is limited to a simple two-station BRT corridor where the stations are connected through road segments. Due to its simplicity, the proposed model only reveals the potential of the simulation framework to model the dynamics of a BRT system.

Moosavi, Ismail, and Golzadfar (2015) outlined the four most important input variables needed for a simulation model of a bus line – segment running time, key stop dwell time, terminal recovery time, and passenger demand – as well as the factors influencing them and having the highest impact on the reliability of high-frequency bus services.

The literature review, comprising various model types, allows us to conclude that regardless of the strengths and the advantages of the models, their practical application is accompanied by some difficulties that can be summarised as follows:

- some models are unnecessarily complex to use and/or include a large number of input variables in them. This makes it hard to find data to feed these models, which makes it difficult to apply them in practice without using specialized computing software and tools;
- some models are developed with specialized software products, which is limiting because: some of these products are expensive to attain, others require programming skills, and for part of the rest it takes a long time to learn and build even relatively simple models. As a whole, the above makes the software hard to use for building and implementing more complex models;
- simplified models that do not describe the system in detail do not give accurate results;
- due to the specifics of the areas for which the models have been developed (such as town architecture, road infrastructure, route characteristics), some models are only applicable to these areas and transport conditions, which means they are not universal and therefore cannot be directly applied or easily reworked and adapted in different case studies;
- “static” models used in modelling a limited number of stop along the route are not flexible as they cannot be adapted for another PT line.
Through the application of the proposed simulation model, which utilises the idea of autonomous vehicles that run on isolated (exclusive) lanes, this work makes an attempt to answer the question Which operational strategy has the potential to improve the reliability of PT service? To do so, we performed simulations under different scenarios and examined the combined impact of parameters such as (i) rate of passenger arrivals at bus stops; (ii) vehicle headway (considered to be a deterministic or random variable); and (iii) vehicle capacity on a) the average waiting time (the most significant measure of transit service reliability) and b) the unserved demand (expressed in terms of the number of passengers who were not transported to their destination point by the end of the simulation).

5.5 Simulation Modelling Framework

5.5.1 Choice of a simulation tool

Of the rich variety of the existing simulation systems, programming languages, and tools reviewed by Borshchev and Filippov (2004) and by Saranova, Poryazov, and Petrov (2010) – general-purpose and specialised – the modern and powerful system for discrete-event and continuous simulation GPSS (General Purpose Simulation System) “World” version for Windows (also known as GPSS W20) was chosen and used as a modelling tool to create a model of a PT line route. An alternative of the GPSS/H21 version, GPSS W, falls into the group of simulation systems for modelling discrete systems. In GPSS the simulation model is built by means of consecutively linked (connected) standard blocks in a block diagram (flowchart) showing the logical structure of the modelled system. The dynamic components in the simulation model are represented by transactions. According to the algorithm's logic, these transactions flow in a sequence (sometimes simultaneously) from one block into another. Each block in the model implements specific functionality – i.e., generating passenger arrivals, simulating queues, servicing facilities (servers), processing times, etc. In addition to the existing functionality, GPSS W allows a user, through the built-in programming language (PLUS – Programming Language Under Simulation), to create and execute his/her own (customised) procedures.

In addition to the above, it is worth mentioning that the GPSS World simulation system can be distinguished due to the following advantages:

- the student version of GPSS World is free to use;
- GPSS W has no high system requirements in terms of hardware. The installation file is small in size, which makes it easy and quick to install on the Windows operating system;
- the Graphical User Interface of GPSS W is user-friendly;

20 http://www.minutemansoftware.com/
21 http://www.wolverinesoftware.com/GPSSHProducts.htm
• GPSS W is accompanied by two manuals, the Reference manual\textsuperscript{22} and Tutorial manual\textsuperscript{23}, which provide readers with solid theoretical knowledge and contain plenty of practically oriented sample simulation models, which accelerates the learning process and makes the work with the system more effective;

• GPSS W provides the users with the possibility to write, save, and keep the program source code in files that are easy to read with simple text editors, such as “Notepad” for Microsoft Windows\textsuperscript{24};

• the program code of the model compiles very quickly – it takes only a couple of seconds to compile and execute even complex simulation models;

• as already mentioned, GPSS W is equipped with a built-in programming language (PLUS) allowing users to use functions and probability distributions as well as enable them to create their own customized procedures, thus extending the capability of the systems and making the simulation model that is developed more powerful;

• GPSS W provides graphical tools and reports enabling users to represent the simulation output results and further analyse them;

• GPSS W also enables users to:
  ✓ generate arbitrary sequence of random numbers by means of the built-in random-number generators;
  ✓ perform repetitive realizations (implementations) with the model;
  ✓ check (debug) the program source code for errors;
  ✓ observe the flow of the dynamic components (transactions) from one block to another during the simulation in accordance with program’s logic as well as to perform stepwise simulation in a sequence of steps;
  ✓ automatically build a journal (log file) showing the history of the events;
  ✓ produce detailed reports containing the simulation output results including values of the system’s parameters evaluated during the simulation as well as descriptive statistics and representation of the simulation results in tables;
  ✓ build histograms representing the probability distributions of the random variables modelled.

5.5.2 Simulation model description

The simulation model developed is composed of the following four segments:

• the “Declaration segment” is used to declare constants, variables, saved (accumulated) values,
functions, procedures, queuing systems' servers capacities, matrices containing in-vehicle travel times, and number of passengers who board/alight buses going through each bus stop;

• the “Passenger arrivals” segment models passenger arrival at each bus stop. This is the segment that models and implements the main logic of the passenger transportation process. Each of the bus stops along the route has been modelled from two different perspectives: that of passengers and that of vehicles:
  ➢ from the passengers' point of view, the bus stops have been modelled with a queue characterised with an incoming flow of passengers whose inter-arrival times follow a specific probability distribution (Uniform, but Poisson arrivals can also be modelled), which remains unchanged during peak hour. The average time in the queue represents the average time a passenger spends waiting at the bus stop for a vehicle to arrive;
  ➢ from the point of view of the vehicles, since in theory more than one vehicle could arrive at the bus stop at a time, bus stops were modelled as multi-server devices capable of “accommodating” a predefined number of vehicles. Since vehicles are not “allowed” to stay outside the bus stop, the “bus bunching” phenomenon and waiting delays in waiting for other buses to leave the stop can be avoided.
• the “Simulation clock” segment controls the duration of the simulation and number of the realizations of the model;
• the “Procedures” segment is where two procedures are called during the simulation when a bus arrives at a bus stop with the purpose:
  ➢ of checking for the maximum possible number of passengers (if there are any at all) who can board the bus depending on the vehicle's capacity, thus making sure that the bus capacity is utilised as much as possible and ensure that the number of passengers who board the bus does not exceed the available vehicle's capacity (depending on how many passengers are already on the bus);
  ➢ of checking for the number of passengers getting off the bus at each bus stop, thus making sure that the number of passengers who get off the vehicle does not exceed the number of passengers in the vehicle.

Each vehicle that has a unique number has been modelled as a multi-server queuing system for which the server's capacity represents the vehicle's passenger capacity, and the servicing time is the in-vehicle travel time. The interesting factor is that in this case the server (i.e., the bus) is a dynamic element that travels through the route while servicing (transporting) the passengers.

An illustrative scheme of the system modelled is displayed in Fig. 5.1, a flowchart of the algorithm of the simulation model developed is shown on Figure 5.2, and the program source code of the simulation model is provided in Appendix C.
The following are minor weaknesses of the model:

- the model does not include the influence on the dwell time of the time it takes for the vehicle’s doors to open/close when it arrives at (or leaves) a bus stop. Since these times (for large boarding/alighting passenger rates as the model uses) are a small percentage of the total dwell time, we disregard their impact. Thus, in the model, the average accumulated dwell times along the whole route for each scenario are estimated as the difference between the average total travel time and the total in-vehicle travel time;

- the model does not take into account traffic signals, which do not affect the simulation results as the model reproduces the PT service provided by vehicles assumed to be autonomous (no drivers) and travelling in exclusive lanes (no intersections and vehicular traffic);

- although the model simulates the passenger transportation process in one direction, the movement of vehicles in the reverse direction can be easily modelled in the same way in a separate GPSS W file or within the same model file after some minor changes are made regarding the section lengths (which affect travel times between stops) and the number of passengers arriving at/departing from these stops;

- the model does not provide information on each passenger with regard to the origin and destination stops of his/her trip along the route. Instead, it provides passenger arrival rates (number of passengers boarding and alighting the vehicles) at each stop and information about the vehicles' load (passenger flow) and utilisation, which could be useful for forecasting purposes, as the results would facilitate the PT planning process.
In contrast to some of the models reviewed, the proposed simulation model and proposed approach utilising autonomous buses travelling in exclusive lanes have the following advantages:

- since the route of the modelled PT line travels in an isolated lane, which is separate from the other transport vehicles, factors such as traffic congestion as well as traffic signals or pedestrian crossings do not affect the vehicles’ movement (nor the in-vehicle travel time between the bus stops). Therefore, possible delays are avoided, and the PT service is reliable, thereby making it more attractive to passengers;
• the concept of operating autonomous vehicles excludes the need for more bus drivers, which would save on operator costs for wages, especially in the case of high frequency service;

• in contrast to models designed to service a fixed number of stops (making the model to seem “static”), the proposed model is flexible, and with just small modifications, it can quickly be reworked and adapted for a route with different characteristics, such as number of stops, section lengths, passenger demand, vehicles' parameters (speed, capacity, and number of doors) as well as some operational parameters (vehicles’ headway and frequency, etc.);

• the model is easily applicable in practice since it requires data for a small number of input variables: (i) route’s characteristics (number of stops, in-vehicle travel time between stops); (ii) vehicle’s characteristics (capacity, including passengers seats, number of doors, and travel speed); (iii) passenger demand-related characteristics (number of passengers arriving at PT stops in accordance with a predefined probability distribution as well as the number of passengers boarding and alighting each vehicle at each bus stop);

• the student version of the simulation system GPSS W used to develop, build, and run the simulation model is free to acquire, and it takes less time to learn than other systems. It is easy to use due to the fact that it is interactive and enables interpretation and analysis by providing reports of the simulation output results through the statistics gathered;

• the model enables evaluation of the performance and efficiency of the PT line and planning of the PT service on a line – for example: based on the maximum vehicle's load (passenger flow) along the route (evaluated as a result of the simulations performed), the model enables PT planners to analyse how the provided vehicle's passenger capacity is utilised, which can help them to identify the minimum required passenger capacity of the vehicle and the required bus headway. The latter allows them to efficiently plan the service with a reduced number of vehicles doing the same job;

• as the model reproduces (replicates) systems’ parameters with a significantly high level of accuracy, it can be applied in a scenario examining the system's behaviour when working with varying passenger demand (and vehicle load) under uncertainty, i.e., when parameters such as passenger arrivals and vehicle headways (used together or separately) are modelled as random variables following a predefined probability distribution (as is the case in real-life systems) as well as to model the PT service on more than one line within a PT network.
5.6 **Numerical Example**

The simulation model was applied on a numerical example considering a PT (bus) line passing through six stops. The input data used to feed the model was:

- duration of the simulation, seconds;
- number of bus stops;
- in-vehicle travel times between stops calculated for predefined distances (sections lengths) and average travel speed, km/h;
- number of passengers boarding/alighting the vehicle at each stop during the simulated period of time (peak-hour);
- boarding and alighting times per passenger, seconds;
- bus headway, seconds;
- bus capacity, passengers;
- bus stations capacity expressed with the number of buses each stop can accommodate.

The output data comprises:

**Stops:**

- maximum and average number of passengers who waited for a vehicle at each stop as well as the number of passengers at each bus stop at the end of the simulation;
- total number of passengers who arrived at each bus stop during the simulated window of time according to the demand;
- average passenger waiting time at each bus stop;
- average time spent boarding/alighting the vehicle at each stop along the route.

**Vehicles:**

- maximum and average number of passengers in each vehicle (vehicle's load) during the simulation as well as utilisation of vehicle capacity;
- rate of unused passenger capacity at the end of the simulation;
- vehicle capacity that is in use at the end of simulation;
- total number of passengers who boarded each vehicle during the simulation;
- total number of passengers who boarded all the vehicles during the simulation (which does not necessarily equal the total number of passengers who arrived at the bus stops);
• total number of passengers who alighted all the vehicles during the simulation;
• total number of passengers who have not been served (transported) by the end of the simulation;
• total in-vehicle travel time along the whole route from bus stop 1 to bus stop 6;
• total dwell time accumulated along the whole route.

5.6.1 Scenarios

The duration of the simulation during which the developed model has been used to simulate the passenger transportation process, on the numerical example with sample values, is 1.2 hours which includes time allowing vehicles to enter the modelled system, namely the route of a bus line and start carrying passengers between the bus stops.

Four scenarios have been created and implemented with the model to simulate the headway-based PT service provided to passengers:

Scenario 1: This scenario considers the passengers’ transportation process along the examined bus route serviced by six buses, each with a capacity of 200 passengers, running with a 10-minute headway (frequency: 6 vehicles per hour).

Scenario 2: This scenario considers the passengers’ transportation process along the examined bus route serviced by ten buses, each with a capacity of 120 passengers, running with a 6-minute headway (frequency: 10 vehicles per hour).

Scenario 3: This scenario considers the passengers’ transportation process along the examined bus route serviced by twenty buses, each with a capacity of 60 passengers, running with a 3-minute headway (frequency: 20 vehicles per hour).

Scenario 4: This scenario considers the passengers’ transportation process along the examined bus route serviced by thirty buses, each with a capacity of 40 passengers, running with a 2-minute headway (frequency: 30 vehicles per hour), thus operating in a metro-like way corresponding to the “think tram – drive bus” concept (Nielsen & Lange, 2008).

5.6.2 Input data and assumptions

5.6.2.1 Assumptions regarding passengers’ demand

Passenger arrivals

Uniformly distributed passenger inter-arrivals times at bus stops were modelled. In order to introduce uncertainty, the model proposed allows simulating passenger arrivals according to a predefined probability distribution such as Poisson distribution (Kirkup, 2002).
Passenger demand

The number of passengers boarding/alighting at each bus stop along the bus line route over the simulated period of time is shown in Table 5.1 and illustrated in Figure 5.3.

**Table 5.1. Passenger demand at bus stops (boarding/alighting passengers)**

<table>
<thead>
<tr>
<th>Bus stops</th>
<th>Passengers boarding</th>
<th>Passengers alighting</th>
<th>Sections, i-j</th>
<th>Distance, km</th>
<th>In-vehicle travel time, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>100</td>
<td>1-2</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>200</td>
<td>2-3</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>300</td>
<td>3-4</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>400</td>
<td>4-5</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>500</td>
<td>5-6</td>
<td>2.0</td>
<td>180</td>
</tr>
<tr>
<td>Total:</td>
<td>1500</td>
<td>1500</td>
<td>10.00</td>
<td>900</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.3. Number of the passengers boarding/alighting the bus along the route during the simulated period of time**

Adebisi (1986) found that although alighting takes less time than boarding, the difference between the two times is less than half a second per passenger.

Assuming that parameters such as travel time, passenger demand, number of transferring passengers, and dwell time are deterministic, in compliance with Dueker, Kimpel, Strathman, and
Callas (2004), Ceder, Hadas, McIvor, and Ang (2013) set default values for the passenger boarding and alighting times to be equal to 3.5 and 2.2 seconds, respectively.

According to Cats, Larijani, Ólafsdóttir, Burghout, Andreasson, and Koutsopoulos (2012) dwell time at the stops along with departure time at origin stations and travel time between stops is one of the sources of uncertainty in public transit operations.

Liu and Ceder (2016a, 2016b) accepted values of 4.0 seconds and 2.0 seconds, respectively, for the marginal dwell times per each boarding and alighting passenger.

Nesheli and Ceder (2015, 2016) applied models to case studies in which they set values of 2.5 and 1.5 seconds for the boarding and alighting of each passenger.

Tang, Ceder, Zhao, and Ge (2016) set values for boarding and alighting times per passenger to 2 and 1 seconds, respectively.

Taking into account the finding of Adebisi (1986) and that the vehicles used in the developed model presented in this chapter have no steps, values of 2.0 seconds and 1.5 seconds, respectively, were assigned for boarding and alighting the bus.

**Dwell time**

In some research works dwell time is considered deterministic (Liu & Ceder, 2016a) or fixed (Adebisi, 1986), while in others it is considered a dependent variable in function of the number of boarding passengers and alighting passengers during different times of the day and along different route types (Dueker, Kimpel, Strathman, & Callas, 2004).

Dueker, Kimpel, Strathman, and Callas (2004) examined and analysed the determinants of dwell time – passenger activity, lift operations as well as low-floor bus, time of day, and route type. In order to evaluate dwell times under different operating conditions Dueker et al. used a model that enabled modeling dwell time at different times of the day, different route types, and various number of passengers boarding and alighting a vehicle.

As Liu and Ceder (2016a) solved the timetable-planning problem rather than an operations-related one, they considered the dwell time as deterministic, and not time-varying within the planning period.

Liu, Deng, and Yi (2011) concluded that “bus dwell time contributes to travel time and headway variation”.

As defined in the Highway Capacity Manual cited by Dueker, Kimpel, Strathman, and Callas (2004), dwell time is “the time in seconds that a transit vehicle is stopped for the purpose of serving passengers. It includes the total passenger service time plus the time needed to open and close
doors”, and therefore it is not constant. It depends on the number of passengers boarding/alighting and the time it takes for each passenger to get on/off the vehicle. Therefore, in contrast to some models in which the dwell time is constant, in the model proposed in this chapter it is in function of the number of passengers wanting to board/alight the vehicle, i.e., the larger the number of the passengers alighting/boarding the vehicle, the larger the dwell time, which sometimes forces vehicles to stay at the bus stops longer than in the models with a deterministic dwell time, thereby making the model more realistic.

5.6.2.2 Operational characteristics

PT line and route characteristics

The PT route servicing the modelled bus line has total length of 10 km. There are six stops in total along the route – two terminal stations and four intermediate bus stops. The route sections connecting the stops along the route are each 2 km long.

Vehicles

Depending on the scenarios played (Table 5.2), the values for the frequency of the vehicles (Ceder, 2007, 2016) and bus headway varies from 6, 10, 20, and 30 vehicles (buses) going one after another with headways of 10, 6, 3, and 2 minutes, respectively. For the purposes of the simulation, buses with total capacity of 200, 120, 60, and 40 passengers (including seats and standing room) were considered for scenarios 1-4. The buses running along the route while servicing the bus line, depending on the vehicle’s capacity, are equipped with 4, 3, and 2 doors for scenarios 1, 2, and 3-4, respectively. The accepted discipline of servicing passengers is such that they can board the vehicle through all the doors available including the front, intermediate (if any), and rear doors.

Operating speed and sections travel times

The in-vehicle travel times along the sections between the bus stops is calculated for a distance between the bus stops equal to 2.0 km and bus operating speed (Vuchic, 2005) equal to 40 km/h.

Based on the above, the main assumptions that have been made can be summarised as follows:

• vehicle headway is deterministic, i.e., it does not reflect any possible deviations due to traffic congestion (although the model enables modelling it as a random variable);

• passenger arrivals at bus stops are uniformly distributed throughout the modelled period of time;

• at bus stops passengers get on the first arriving vehicle. If the arriving vehicle is full, then passengers get on the next vehicle (which results in increased waiting time);

• the bus does not leave the bus station before all the passengers have boarded as long as the
available vehicle capacity allows this to happen;

- since buses run along a lane considered isolated (separated) from the other vehicular traffic, there is no traffic congestion and traffic signals incurring delays;
- since buses go one after another according to the sequence by which they have entered the system (route), keeping a distance (one headway), one bus cannot bypass another.

A comparison of the observed (actual) and the simulated (reproduced) number of passengers who alighted the vehicles at each stop along the route of the examined bus line is shown in Figure 5.4 (a,d).

![Graph](image)

(a) Observed and simulated passengers who alighted at each bus stop in scenarios 1 and 2 (Fig. 5.4(a) and 5.4(b), respectively)

![Graph](image)

(b) Observed and simulated passengers who alighted at each bus stop in scenarios 3 and 4 (Fig. 5.4(c) and 5.4(d), respectively)

Figure 5.4. Total observed and simulated passengers who alighted at each bus stop in scenarios 1-4 ((a)-(d), respectively)

The simulated average waiting times at each bus stop, excluding stop 6, which is the last for the route, for each of the above four scenarios are shown in Figure 5.5 below.
The simulated average waiting times were compared with those that were analytically calculated by the formula:

\[
AWT = \frac{(AWT_{\text{max}} - AWT_{\text{min}})}{2} = \frac{H}{2}, \text{ seconds, where:}
\]

\(H\) – vehicle (bus) headway (Ceder, 2007), i.e., the time interval between two vehicles going along the route;

\(AWT_{\text{min}}\) – the minimum time (in seconds) passengers wait the vehicle at the bus stop, which is \(AWT_{\text{min}} = 0\) seconds when a passenger comes at the time when bus arrives;

\(AWT_{\text{max}}\) – the maximum time (in seconds) passengers spend waiting when they arrive at the stop at the moment the bus departs the stop. In that case, passengers need to wait for the next bus, which arrives after time equal to \(H\).

Let us, for example, consider scenario 1 in which the bus headway is 600 seconds (10 minutes). Theoretically, the minimum time each passenger will wait for a bus at the bus stop is \(AWT_{\text{min}} = 0\) seconds and the maximum is \(AWT_{\text{max}} = 600\) seconds; on average a passenger waits 300 sec., i.e.:

\(AWT = \frac{(600 - 0)}{2} = 300\) seconds, which is almost equal to the average waiting time of 339 seconds evaluated as a result of the simulations performed as a weighted average of the passenger waiting times at the bus stops along the route. For scenarios 2-4, the analytical average waiting times have values:

\(AWT = 180\) seconds for scenario 2, \(90\) seconds for scenario 3, and \(60\) seconds for scenario 4.
The above formula (5.1) does not take into account:

- any possible deviations due to bus delays or early arrivals;
- the time passengers spend due to a missed bus, i.e., if they have waited $AWT_{max}$ for the bus, and after the bus has arrived if they did not board because the vehicle was full.

The average dwell time (ADT) shown in table 5.2 below accumulated along the whole route was calculated as a difference between the average total travel time (ATTT) from the first to the last bus stop and the total in-vehicle travel time (TIVTT).

As can be seen in table 5.2, the comparison between the simulated weighted average waiting times and those times calculated via formula (5.1) shows that the model satisfactorily reproduces the waiting times at all bus stops along the route.

**Table 5.2. Scenarios played (Direction: From bus stop 1 to bus stop 6)**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Vehicle frequency, buses per hour</th>
<th>Bus headway, seconds</th>
<th>Vehicle capacity, number of passengers</th>
<th>Number of doors</th>
<th>Average total travel time along the whole route (ATTT), seconds</th>
<th>Standard deviation of ATTT, seconds</th>
<th>Total in-vehicle travel time (TIVTT), seconds</th>
<th>Estimated average dwell time (ADT) accumulated along the whole route, seconds</th>
<th>Simulated weighted average passengers waiting time at each bus stop, seconds</th>
<th>Analytically calculated average passengers waiting time at each bus stop, seconds</th>
<th>Evaluated number unserved passengers along the route</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>600</td>
<td>200</td>
<td>4</td>
<td>1070</td>
<td>5.9</td>
<td>900</td>
<td>170</td>
<td>339</td>
<td>300</td>
<td>112</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>360</td>
<td>120</td>
<td>3</td>
<td>1035</td>
<td>4.9</td>
<td>900</td>
<td>135</td>
<td>209</td>
<td>180</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>180</td>
<td>60</td>
<td>2</td>
<td>1001</td>
<td>3.7</td>
<td>900</td>
<td>101</td>
<td>109</td>
<td>90</td>
<td>51</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>120</td>
<td>40</td>
<td>2</td>
<td>968</td>
<td>3.8</td>
<td>900</td>
<td>68</td>
<td>76</td>
<td>60</td>
<td>46</td>
</tr>
</tbody>
</table>

1 Includes the total passenger seats and the total number of standees

2 Weighted average passenger waiting time calculated as a weighted sum of the simulated average waiting times at bus stops multiplied by the number of the passengers waiting these times

3 Number of unserved passengers calculated as a difference between the total simulated passengers who boarded and alighted

Below are charts showing the relationship of the simulated average waiting time in function of vehicle frequency (Figure 5.6) and the dwell time in function of bus capacity (Figure 5.7) for scenarios 1-4.
Based on the results above, it can be concluded that variant 4 (with high-frequency, small-size vehicles) would not only provide PT users with decreased average waiting times due to the small bus headways, but also with reduced total travel times along the route due to the operation of small-capacity vehicles spending less dwell times at bus stops. Moreover, as can be seen on Figure 5.8 below, in contrast to the 3 other scenarios, the high frequency small-vehicle service (scenario 4) results in the lowest number of 46 unserved passengers (those who have not alighted and are still traveling in the vehicles at the end of the simulation), followed by scenario 3 with 51 passengers, and scenarios 2 and 1 with 63 and 112 passengers, respectively. In other words, compared to the scenario 1, in scenario 4 the number of the unserved passengers is more than 2 times less.
If we consider in detail the simulation output results for scenario 4, it can be seen (Table 5.3 and Figure 5.9) that the PT operator satisfies PT demand entirely with a large number of small-size vehicles. The minimum and the maximum bus load along the sections are 24 and 36 passengers, which expressed as a percentage is 60% and 90% capacity utilisation, respectively. The average bus load is 29.3 passengers, which represents a capacity utilisation of 73.3%, indicating that around ¾ of the available passenger capacity is used. The model was used to evaluate and analyse the vehicles’ capacity utilisation (Table 5.4 and Figure 5.10) in a scenario with a reduced by 20% number of operating vehicles (from 30 to 24 buses) and reduced frequency in which the bus headway has been increased by 25% from 2 to 2.5 minutes. The purpose of this scenario was to answer the PT planners’ question What is the number of vehicles and the time interval between them that meet the existing PT demand, thus allowing PT planners to achieve improved bus utilisation and a small number of unserved passengers at the price of slight (but still acceptable) increase of average passenger waiting time?

Figure 5.8. Number of the passengers who have not been served by the end of the simulation
Table 5.3. Scenario 4: 30 vehicles with capacity of 40 passengers going along the route with a 2.0-minute headway

<table>
<thead>
<tr>
<th>Vehicle #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle capacity</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
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<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Utilisation, %</td>
<td>87.5</td>
<td>70.0</td>
<td>77.5</td>
<td>70.0</td>
<td>65.0</td>
<td>85.0</td>
<td>90.0</td>
<td>70.0</td>
<td>70.0</td>
<td>77.5</td>
<td>70.0</td>
<td>70.0</td>
<td>77.5</td>
<td>72.5</td>
<td>72.5</td>
<td>72.5</td>
<td>72.5</td>
<td>72.5</td>
<td>72.5</td>
<td>90.0</td>
<td>70.0</td>
<td>77.5</td>
<td>70.0</td>
<td>77.5</td>
<td>67.5</td>
<td>72.5</td>
<td>77.5</td>
<td>67.5</td>
<td>72.5</td>
<td>77.5</td>
</tr>
</tbody>
</table>

Table 5.4. Scenario 4.1: 24 vehicles with capacity of 40 passengers going along the route with a 2.5-minute headway

<table>
<thead>
<tr>
<th>Vehicle #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
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<th>17</th>
<th>18</th>
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<th>23</th>
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<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Vehicle capacity</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
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<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Maximum load</td>
<td>40</td>
<td>33</td>
<td>40</td>
<td>34</td>
<td>31</td>
<td>40</td>
<td>40</td>
<td>31</td>
<td>40</td>
<td>37</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>36</td>
<td>35</td>
<td>37</td>
<td>36</td>
<td>36</td>
<td>30</td>
<td>35</td>
<td>35</td>
<td>35</td>
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<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Utilisation</td>
<td>100.0</td>
<td>82.5</td>
<td>100.0</td>
<td>85.0</td>
<td>77.5</td>
<td>100.0</td>
<td>100.0</td>
<td>77.5</td>
<td>100.0</td>
<td>92.5</td>
<td>100.0</td>
<td>100.0</td>
<td>67.5</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>90.0</td>
<td>100.0</td>
<td>87.5</td>
<td>100.0</td>
<td>92.5</td>
<td>100.0</td>
<td>90.0</td>
<td>90.0</td>
<td>90.0</td>
<td>90.0</td>
<td>75.0</td>
<td></td>
</tr>
</tbody>
</table>

The scenario with reduced number of vehicles (from 30 to 24, i.e., by 20%) and increased bus headway from 120 sec. to 150 sec. (25% increase) led to an increase in the average passenger capacity utilisation of the vehicles from 73.3% (29.3 passengers on average on the bus) to 92% (36.8 passengers on the bus), which is around a 20% increase at the cost of increased average passenger waiting time at the bus stops along the route from 76 seconds to 114 seconds (by 50%). The number of the unserved passengers has slightly decreased from 46 to 40 (13% decrease), which is insignificant and can be ignored. The average total travel time remains almost unchanged – it has been slightly increased from 968 to 985 seconds.

Figure 5.9. Maximum vehicle capacity utilisation reached by vehicles along the bus route (scenario 4)
As can be seen in Figure 5.11 and Figure 5.12 below representing the passenger load in vehicle #7 (in scenario 4 with 30 buses running one after another with 2-minute headway) and vehicle #3 (in scenario 4.1 with 24 buses running one after another with 2.5-minute headway) even for the most-loaded vehicle #7 (Figure 5.11) the maximum bus capacity utilisation has not been reached. The higher passenger load has been observed in 1 of the 5 route sections (#3 between stops 3 and 4). In contrast, in the scenario with 6 fewer vehicles (24 rather than 30 buses) for vehicle 7, which is 1 out of 12 vehicles whose capacity has been reached (for half of the vehicles along the route, the maximum passenger capacity has been reached), is highly loaded in more than one section (section 3-4 between stations 3 and 4, followed by section 4-5 between stops 4 and 5). This shows how the proposed decreased number of buses running leads to better vehicle utilisation.
The above example shows the power of the model that could be easily applied for planning the operations along a PT route. In the example considered, the application of the model helped to better plan the PT service with reduced vehicle frequency, which resulted in higher vehicle utilisation (operator’s benefit), acceptable increase of the average passengers waiting time (user’s benefit), negligible change in the average total travel time, and insignificantly decreased number of the unserved passengers along the route.

5.6.3 Simulation model – calibration and validation (Jaspers Appraisal Guidance, 2014)

An advantage of the proposed simulation model, which would make it easily applicable, is that it does not include a large number of input variables. In contrast to some complex mathematical models (having objective functions subject to different constraints – linear and non-linear), the calibration of the model did not involve optimisation criteria that needed to be met. That is why a search method has not been applied and computational performance has not been evaluated. A non-iterative approach for the model’s calibration was used instead.

The calibration parameters used were:

- Rate of passenger arrivals – an average number of passengers alighting the vehicles at each bus stop and calculated in function of the vehicle frequency for each scenario;
- Average interarrival times of passengers at each stop along the route of the modelled PT line;
- Number of serviced passengers (boarded and alighted) in the vehicles going along the bus route for the duration of the simulation.

The calibration criteria on the one hand was to what extent the simulation model reproduces the PT demand (passenger arrivals at bus stops along the route and the process of leaving bus stops
as soon as passengers aboard the vehicles) and on the other hand – a comparison was made of the “observed” (sample) ground truth data used and the simulation model output regarding passengers boarding and alighting vehicles at the bus stops along the PT bus route, i.e. identifying how close in terms of the value was the total number of passengers served (boarded/alighted) during the simulation (simulated period of time) on each bus stop compared to the served ones in the numerical example.

In order to calibrate the model, some of the model's parameters, such as the number of passengers who boarded/alighted the vehicle at each bus stop along the route and the total number of passengers who boarded/alighted for the whole route during the simulated period of time were adjusted until the model estimates became as close as possible to the observed data. Scenario 1 was used as the base scenario during the calibration process.

As a validation check of the model served the comparison between the simulation model’s output data and the observed data (as per the provided numerical example) performed through a Goodness-Of-Fit test in the form of a linear regression analysis (Kirkup, 2002) for the considered scenarios. The validation variable was the observed (“actual”) passengers who alighted the vehicles at the bus stops along the PT bus line for the modelled time window versus the simulated number of passengers who alighted (Figure 5.13 (a,d)). The coefficient of determination, $R^2$, having value above 0.96 (very close to 1), demonstrated that with a satisfactory level of accuracy the model replicates the “real-life” (observed) data.

Similar to Chapter 4, the existence of a significant relationship between the independent and the dependent variables $X$ and $Y$ for sample data was estimated through the relationship in the derived linear regression equations of the type $\hat{y}_i = b_0 + b_1 x_i$. And again, t-tests for statistical significance were performed with the purpose to identify if the slope significantly differs from 0.

The following two hypotheses were checked:

- Null hypothesis, $H_0$: The slope of the regression line is equal to 0, i.e. $b_1 = 0$;
- Alternative hypothesis, $H_1$: The slope of the regression line is not equal to 0, i.e. $b_1 \neq 0$.

The values of the $t$ statistics calculated as a result of the performed regression analysis by using the Data analysis Tool in MS Office Excel as well as the critical value $t_{crit} = 3.182$ obtained from Table 2 (Kirkup, 2002) for critical values of the t-distribution for two-tailed t-test for accepted level of significance $\alpha = 0.05$ and calculated degrees of freedom $df = N - 2 = 5 - 2 = 3$ are summarised in Table 5.5. Again, the critical value $t_{crit} = 3.182$ matches with the value returned by the T.INV.2T($\alpha$,df) Microsoft® Excel’s function having the significance level $\alpha$ and the degrees of freedom $df$ as arguments.
Table 5.5. Summary of the results for the performed two-tailed t-test for statistical significance of the slope with accepted significance level $\alpha = 0.05$ and calculated degrees of freedom $df = 3$.

| Scenario number | Coefficient of determination $R$-square | $b_0$ | $b_1$ | $S_{b_1}$ | $|t|$ | Mathematical operator (“$<$”, “$=$”, “$>$”) | $t_{crit}$ | Reject the null hypothesis $H_0$ (Y/N) | The slope is statistically significant (Y/N) |
|-----------------|-----------------------------------------|-------|-------|-----------|-------|-----------------------------------------|----------|------------------------------------------|------------------------------------------|
| 1               | 0.9803                                  | 36.1  | 0.797 | 0.065     | 12.231| $>$                                     | 3.182    | Y                                        | Y                                        |
| 2               | 0.9935                                  | 15.6  | 0.902 | 0.042     | 21.492| $>$                                     | 3.182    | Y                                        | Y                                        |
| 3               | 0.9978                                  | 15.2  | 0.914 | 0.025     | 36.550| $>$                                     | 3.182    | Y                                        | Y                                        |
| 4               | 0.9604                                  | 53.6  | 0.790 | 0.093     | 8.530 | $>$                                     | 3.182    | Y                                        | Y                                        |
| 4.1             | 0.9741                                  | 58.4  | 0.778 | 0.073     | 10.625| $>$                                     | 3.182    | Y                                        | Y                                        |

Based on the $R$-square values and the results for the performed t-test for statistical significance of the slope it can be concluded that for all the scenarios the null hypothesis needs to be rejected and the alternative one should be accepted, which proves that the slope is statistically significant and therefore there exists a significant linear relationship between the dependent and independent variables analytically described by the derived linear regression equations.

**Figure 5.13.** Observed versus simulated passengers who alighted the bus in scenarios 1-4 ((a)-(d), respectively)

(a) Observed versus simulated passengers who alighted the bus in scenarios 1 and 2 (Fig. 5.13(a) and 5.13(b), respectively)

(b) Observed versus simulated passengers who alighted the bus in scenarios 3 and 4 (Fig. 5.13(c) and 5.13(d), respectively)
5.7 Conclusions and future work

Based on the analysis of the simulation output results, the following main conclusions can be drawn, and recommendations offered:

Although the choice of a modelling framework depends on the purpose of the work, the characteristics of the system, and the existing constraints, models should:

• be easily implementable within at least some of the existing simulation systems, languages, and tools;
• be detailed enough to describe the system, reproduce the system’s processes, and give accurate results;
• have a small number of input variables, which would make it possible to feed the model with data and directly apply it in practice;
• be easily maintainable, which would allow modelers to quickly adapt the model for different PT routes and transport conditions.

It turned out that among the large variety of existing simulation systems, programming languages, and tools, the GPSS World simulation system, used in this work, is a powerful tool enabling modellers to precisely design, easily build, and quickly implement a very flexible (in terms of the possibilities to be extended), and detailed enough model; after compiling for a couple of seconds, it provides modellers with output results and accumulated statistics in the form of generated reports that present the results in tables and graphs.

In light of the rich variety of simulation models and tools, this simulation model stands out because of:

• the small number of input variables, which makes the model’s usage and subsequent application realistic;
• its flexibility, which enables, through minor modifications, relatively easily and quickly reworking the model and thus adapting it for modelling the passenger transportation process along a public-transport line characterised with specific parameters with regard to the route, the vehicles carrying passengers, and the variability of passenger demand;
• the ability of the model to enable evaluating the existing system’s performance and efficiency along the route of a PT line under simulation, which would allow PT planners to effectively plan the PT service under different (existing and forecasted) conditions and scenarios.
The results from the simulation scenarios showed that the model satisfactorily reproduces the parameters of the modelled system, which allows us to summarise the simulation output results as follows:

- Among the scenarios, scenario 4 simulating a high frequency, metro-like PT service, due to the small vehicle headways, provides passengers with the least average waiting time at bus stops;

- Due to the small capacity of the high frequency vehicles used, which means less time for boarding/alighting (in contrast to the large-vehicle scenario), scenario 4 offers the lowest estimated average dwell time along the whole PT line;

- The high frequency public-transit service provided in scenario 4 is the one that leaves the smallest number of unserved passengers along the route of the modelled PT line;

- A small decrease in the frequency of the vehicles (less vehicles) when a high frequency, metro-like service is provided leads to an improved utilisation of vehicle capacity (operator’s perspective) at the cost of an acceptable increase in the average passenger waiting time at bus stops (user’s perspective) and insignificant increase of the number of unserved passengers.

A next step in the research would be an application of the concept of multi-agent systems in a case study comprising more than one route in a public transport network with a specific network topology – a subject discussed in detail in Chapter 6.
CHAPTER 6. MULTI-AGENT SIMULATION OF THE PASSENGER TRANSPORTATION PROCESS IN A MONORAIL PUBLIC TRANSPORT NETWORK WITH OPERATING AUTONOMOUS TRAINS: A CASE STUDY

This chapter is derived as a result of a case study carried out in Auckland, New Zealand.

In order to provide PT users with a high-quality PT service, transport operators should regularly apply measures for examining and improving a public transport network, which in turn would allow them to provide transport supply that meets travel demand. The developed models presented in the previous Chapters 4 and 5, although providing promising results, were applied to simulate the public-transit operations along a single route. This directly makes the attained results isolated and only valid on a local level (PT route) and does not guarantee that a partial solution would contribute to improvement of the entire public transport system. Therefore, a whole network should be examined rather than separate routes, which would make it possible to “look at the whole picture”. One of the possible alternatives enabling realising the above intent is an application of the agent-based modelling approach in modelling and simulation of a passenger transportation process along the routes of a public transport network within a MAS with interacting agents. This approach would enable reproduction of the behaviour of the modelled system, exploration of the system’s dynamics, analysis of the ongoing processes, and improvement in the functioning of the whole system and not only a part of it.

Chapter 6 makes an attempt to bridge both network science concepts and tools (applied in chapters 2 and 3) and public-transport operations (simulated in chapters 4 and 5) in a multi-agent simulation of the passengers’ transportation process along the lines with common transfer points into a monorail trains public-transport network characterised with a specific topology.

6.1 Objective and tasks of the case study

The objective of this case study – an application of an efficient controlling strategy in achieving a reliable, punctual and fast PT service – was achieved through solving the following main tasks:

(i) Generate a network with specific topology and features that serves as a fundamental of the subsequently designed route network.

(ii) Adapt the structure of the generated network into Auckland’s urban plan in compliance with the existing road conditions and environmental restrictions, such as roads, streets, residential and business buildings, and others.

(iii) Design a monorail public transport route network with routes going through the generated network exhibiting small-world features and serviced by autonomous trains.
(iv) Perform a multi-agent simulation of the passenger transportation process along the routes of the designed monorail PTN within the modelled MAS consisting of interacting agents with the purpose of achieving a reliable and punctual public transport service.

(v) Conduct a post-simulation analysis, discuss the simulation output results, draw conclusions and outline directions for future research work.

6.2 Literature review of research work devoted to the Agent-based modelling approach and Multi-agent systems

“Agent-based modelling and simulation (ABMS) is a new approach to modelling systems comprised of autonomous, interacting agents” (Macal & North, 2005) that are discrete entities with specific attributes and rules determining their behaviour. Agents possess the ability to learn and play roles enabling them to interact with other agents in an interactive environment.

The role of agent-based modelling (ABM) as a tool that makes it possible to design, create and implement models of complex systems marked significant progress, particularly in the dynamic field of public transport. In the last few decades there have been numerous works such as books, articles, papers and reports, devoted to this comparatively new simulation approach – agent-based modelling and simulation.

According to Brown (2006) agent-based models are computer representations of systems comprised of multiple, interacting actors called agents. Brown writes that the “the process of building ABMs starts with conceptual modelling” (Robinson, 2008) once the purpose and the tasks are set and the elements of the modelled system – the agents with their behaviour and interactions – are identified. And once a computer program of the model is designed, as Brown writes, its software implementation must be written taking advantage of the existing gamma of object-oriented programming languages, such as objective C, C++ and Java or software libraries, such as SWARM, REPAST, MASON, all written in Java or some software packages such as NETLOGO, AGENTSHEETS and STARLOGO. Finally, he notes that before putting the created agent-based model into practice, it must be carefully calibrated (setting the model’s structure and parameter values such that they precisely reflect the real-world situation) and validated (to confirm, by experiments, that the modelled system this model describes, behaves similar to the real-world system), which is the toughest task.

Bernhardt (2007) asserts that ABM is particularly appropriate for exploring the behaviour of complex systems.

Bonabeau (2002) summarised that ABM is best applied when:

- the existing interactions between agents are complex, non-linear, discontinuous or discrete
the positions of agents are not fixed, and more space is needed
agents exhibit complex behaviour, including learning and adaptation

The application of the ABM concept for building models is accompanied by some weaknesses:

- agent-based models need significant volumes of data.
- as agent-based models are computationally intensive, the requirements of computer configurations – CPU (central processing unit) and RAM (random-access memory) – are high.
- sometimes there are difficulties related to the validation of the agent-based models applied to predict the behaviour of systems that have not been previously tested.

With regard to the application of ABM, Bonabeau (2002) suggested that it might be used “when describing the system from a perspective of its constituent units' activities is more natural, when”, as Bonabeau writes, “activities are a more natural way to describe the system than processes”.

This key finding emerged as a result of a panel discussion carried out (Siebers, Macal, Garnett, Buxton, & Pidd, 2010) with the purpose of finding that the answer to the question, “why in comparison with the discrete-event simulation (‘top-down’ approach focused on modelling the system in detail, not entities), agent-based simulation (‘bottom up’ modelling approach focused on modelling entities called agents and their interaction) is not so widely-used?” is that although there is a huge interest towards the utilisation of agent-based simulation (ABS) in both academia (researchers and scientists) and industry (business), still most of the people are not familiar enough with this paradigm and therefore they do not have the knowledge enabling them to apply ABS in their studies. Fortunately, in recent years the situation has changed. There has been significant progress in this domain and the results obtained in research works in this direction are promising.

Similar to the other modelling initiatives, it is important in ABM to define the problem and then to examine whether or not the ABM concept is relevant to use. If the ABM approach seems to be appropriate for the application, then the agents must be defined first: (a) types (cars, buses, drivers, roads, traffic lights), (b) attributes, (c) allowable and initial values for these attributes, then (d) the rules based on which agents will interact with one another, (e) the interaction environments and (f) afterwards a selection of a programming language (C, C++, Java) or agent-based software platforms and methods (Gilbert & Bankes, 2002) that can be either propriety agent-based modelling platforms (AnyLogic) or freely available modelling tools (RePast, Swarm), etc. Conventional programming languages, such as C++, Java, SmalTalk and others, were widely-used for developing models in the early 1990s. However, their use was accompanied by some disadvantages: the modeller must implement the algorithms in the model by writing a program code, which assumes programming knowledge and a reliable compiler, and this makes this task difficult to solve and time-consuming.
In addition, sometimes the graphical libraries and functionalities lack facilities or are poorly suited. Fortunately, similar to the distribution of libraries containing routines (procedures or methods) that can be included in user’s programs in some of the statistical packages (collections of routines assembled within standardized user interfaces such as SPSS and SAS, for example), modellers can use software simulation platforms for agent-based modelling such as REPAST, SWARM and ASCAPE including developed libraries, which excludes the need to write procedures that are already written by others. Such platforms usually go with standard packages of software libraries (some of which are open-source and free to use upon the respective licenses), mainly written in Java (Schildt, 2005), enabling users to build agent-based models, create agents and perform multi-agent simulations, collect simulation output data, graphically represent it and subsequently analyse it. Users can even build their own interface and thus extend a system’s functionality like Grether and Nagel (2013) have done in their recent work, where they show how systems’ possibilities for extension can be used, giving an example for extending MATSim’s functionality (Balmer, Rieser, Meister, Charypar, Lefebvre, Nagel, & Axhausen, 2009) by incorporating a traffic signal control module. These software libraries have great advantages over “rolling your own”, but their utilisation and application requires familiarity and working knowledge of the programming languages they are based on. According to Gilbert and Bankes (2002) “the ideal is a system that requires a minimum of learning, is completely flexible in the models that it will support and runs efficiently on any hardware”. A bright example of such a system, taking advantage of multi-platform object-oriented programming language Java (Schildt, 2005) and covering the above requirements, is the open-source, agent-based simulation framework MATSim (Horni, Nagel, & Axhausen, 2016) designed to perform fast, large-scale multi-agent transport simulation scenarios.

It is obvious from Bernhardt’s work (2007) that ABM has been successfully applied for solving large number complex problems, including traffic simulations and agent-based models the most notable of which are TRANSIMS and MATSim (multi-agent transport simulation). MATSim is a large-scale, Java-based, agent-based traffic simulator (Balmer et al. 2009) which during the last decade has found application for solving various transportation problems, including modelling public transit as a multi-agent system (Weyns & Uhrmacher, 2009). A huge contribution in this direction is the notable work of Rieser (2010). His contribution is mainly in extending MATSim’s functionality by incorporating PT as a mode of transportation. Thus he provided modellers with the opportunity to create large, real-life scenarios and perform multi-agent simulation for complex PTNs in large cities, combining (Rieser & Nagel, 2009) private cars and the integrated PT traffic, which allows passenger agents to make a choice about the mode of transport they will use for their trips on the next iteration, i.e. next simulated day. The latter is a choice made on the basis of the utility function used to score agents’ experiences in travelling with alternative modes of transport.
Moreover, Rieser outlines the perspectives and possibilities for extension of MATSim’s functionality to include multi-agent simulations and other means of transport, such as paratransit.

Laichour, Maouche and Mandiau (2001) use a multi-agent approach aimed to minimise the waiting times of passengers within PTNs. Their model is based on a hierarchical multi-agent system (MAS) composed of three types of interacting agents: (i) supervisor agent (interface) establishing dialogue with the regulator (operator); (ii) connection agent (decision) proposing a set of decisions so as to preserve the stability at connection nodes (transfer stations) in case any disturbance appears; (iii) acquisition agent (perception) for each regulation station, responsible for recording data concerning buses and passengers. The model they propose, incorporating a mechanism capable of predicting incidents at transfer nodes before their emergence, has been used in developing a decision-support system that provides managers with a functionality to exert regulating actions at connection nodes.

Berdai, Gruer, Hilaire, and Koukam (2002) proposed a methodology based on the agent paradigm, which is used for developing a multi-agent model allowing designing, modelling and simulating a public transportation system as a multi-agent system and enabling estimation of passenger transfer waiting times at transfer points, which can be further used as a basis for minimisation of total passenger transfer time. The model suggested is based on the RIO (role, interaction and organisation) approach according to which the modelled system is implemented as composed of three levels – organisational level, agent level (with agents playing roles of buses, stops and transfer nodes) and agent instance level. Although the presented methodology is based on assumptions, such as exponentially distributed (Poisson) passenger arrivals, normal distribution of vehicle movement along the route sections, and passengers getting off the bus at stops at random, according to the authors it constitutes the first step towards multi-agent modelling and simulation of a PT network.

To identify the entities and their interaction of the observed system, Meignan, Simonin, and Koukam (2006, 2007) modelled the PT network as a multi-agent system within which two types of autonomous entities with their own behaviours interact with each other in the environment ‘road network’ that can be a bus or pedestrian network: (i) ‘travel agents’ (playing roles of pedestrians and bus passenger) and (ii) ‘bus agents’ (playing roles of vehicles and transport service). Thus on the one hand Meignan, Simonin and Koukam take advantage of the agent-based approach providing the possibility to represent and model behaviour of multiple agents, and on the other hand the benefits of using agent-based software platforms and methods (Gilbert & Bankes, 2002) designed with the purpose of creating agent-based models. The model they propose to model, simulate and subsequently evaluate the urban transit network incorporates (a) bus operations, (b) a hybrid traffic
simulation model considering the interaction of road traffic consisting of buses and cars and (c) a multinomial logit model for modelling passengers’ modal choice. The simulations with the model, integrated into and implemented with Java decision-support software, are performed on a real-life case study – the PTN in Belfort (France), including eight bus lines operating. The main advantage of the model, that can be used to control the bus network in case some unexpected event occurs (traffic congestion or accident, for example), is that it takes into consideration passenger behaviour as well as some features characterising vehicle operating into PT.

Jin, Itmi, and Abdulrab (2007) used the agent-based approach in order to design and implement an intelligent traffic information control system, representing it as a MAS with four types of interacting agents: (i) user agents (representing human users with their assigned roles and interaction), (ii) plan agents (agents responsible for receiving, processing, assigning and scheduling vehicles according to customers’ requests for trips), (iii) trip agent (modelling the vehicles running in the system) and (iv) broker agent (playing the role to match trip requests with the existing transport supply, i.e. available vehicles, excluding the assignment of these requests to vehicles). The proposed multi-agent framework, implementing decision responsive transport services dealing with the assignment and scheduling of users’ trip requests to vehicles available, consists of three layers: (i) agent platform (implemented on JADE software), (ii) a multi-agent architecture and (iii) urban traffic information system. Three model implementations have been proposed: (1) a centralised model aimed to optimise the whole system. It is focused on minimisation of the operator’s disutility (number of vehicles and hence the operator’s costs incurred) and total passenger waiting time; (2) a decentralised model. Each agent aims to maximise its own utility, which results in an excess in waiting and travel times; (3) a hybrid model, which according to what is reported, seems to be the best one, as it fills the gaps in performance between the first two models. Compared to the centralised model, the hybrid model provides better results for clients, regarding the excess in travel time, and compared to the decentralised one, it results in a better waiting time. As a whole, however, the hybrid model is the more stable model, which is considered as its main advantage.

In order to reduce the level of uncertainty in simultaneous arrival of vehicles at transfer points and increase the number of simultaneous transfers, thus reducing passenger transfer waiting time, Hadas and Ceder (2008) applied a newly developed passenger transfer concept extending the well-known single-point encounter (passengers change vehicles at transfer stops) to a new one – a road-segment encounter (any point along routes segment is a potential transfer point for passengers). This idea is implemented by using a multi-agent approach to model a public transit system as a MAS (Fig. 6.1) with five types of agents interacting with each other: (i) passengers’ agents, planning through a smartphone software application their trips on the basis of the available online real-life information about road agents (traffic conditions and travel time) and vehicle agents
(routes, bus load and dwell time); (ii) road segment agents that, depending on their location, can be a traffic light controller as part of the road structure or part of a multi-agent software system (being in this case responsible for travel time and encounter probability estimation); (iii) vehicle agents, playing a role to estimate the dwell time based on the current transport demand and evaluate the timetable’s deviations (behind or ahead schedule); (iv) operator agent (responsible for the route network design, providing transport supply, updating the existing timetables and deploying operational tactics at stops or along the road segments; (v) authority agent, implementing control over the system, monitoring the system’s performance and observing its performance indicators.

Figure 6.1. MAS-Based Public Transit System (Hadas & Ceder, 2008)

The proposed MAS approach incorporates three models: (i) a simulation model developed to estimate the encounter probability; (ii) a distributed DP optimisation model with the objective to minimise the total passenger travel time in the system; (iii) a simulation model used to validate the optimisation model. The suggested multi-agent concept has been applied on an example network representing a real situation with one main bus line connected to a train line and two feeder bus lines. The whole network has 14 road segments. The simulation under different parameters, with synchronized and non-synchronized timetables, has been performed for three scenarios without optimisation, with centralised DP optimisation and with distributed DP optimisation. According to the results the application of the newly developed multi-agent concept including deployment of a
hold, skip-stop and hold road-segment operational tactics, has led to a decrease in average travel time of 7% and to a significant increase in the total number of direct (simultaneous) transfers of up to 285%. Moreover, both the optimisation scenarios are better than that without any optimisation, and the centralised DP scenario outperforms the distributed DP scenario, but at the price of its complexity.

Recently Li, Zhang, Wang, Lu, and Mu (2011) argued that in order to coordinate transit modes the following two different tasks must be solved: (i) integration of the networks of both transit modes – bus and subway train – on a strategic level and (ii) timetable coordination on a tactical level. As a possible alternative for simulating a complex system such as PTN and dealing with the above tasks, Li and his colleagues use the agent-based software AnyLogic, to develop a framework of an artificial urban transit system with two types of environment (stations/stops and home/work) and three types of agents interacting within these environments: passengers’ agents (taking decisions regarding the mode of transport and the departure time based on information about the PTN scheme), buses and subway with the respective capacity, playing two roles: (i) running along segments between the stations with different frequencies and speeds or (ii) loading/unloading passengers at stations. The main difference between bus agents and train agents is expressed in terms of the ability of buses to adjust to route changes. For the purposes of the experiments implemented on a desktop PC with 1.8GHz CPU and 2.0G DDR-II memory, the authors use as a case study a simplified version (part) of PTN in Beijing (China) including 3 bus lines. The results reported after the test scenarios have been played – forecasting transit demand and evaluating a new route added – assigning different bus capacities and frequencies, are promising, throwing out a hint about the potential of the developed system to support public transport route network planning and operations. The superiority of the system involves agents’ day-to-day learning (choice of a mode and route as well as departure time, based on agent’s experience). It considers a dynamic (variable) demand (O-D matrix) and enables performing simulation with running vehicles with different capacities and frequencies as well as it being able to take into account the changing traffic and the potential for traffic congestion.

In a more recent study to model the interaction between passengers with dynamically changing travel demand and the transit system providing transport supply, Cats (2013) used the agent-based approach to develop a dynamic multi-agent framework which models the interaction of autonomous agents and simulates transit operations. The framework comprises integration of components, such as population generator, traffic and transit operations simulator, dynamic path choice model, real-time processor of information as well as adaptive transit operations planning. The multi-agent framework is implemented in the working environment and implements the transit simulation model BusMezzo.
To measure the operation’s performance of a competing fixed and flexible (users-responsive) public transport service, Narayan, Cats, van Oort, and Hoogendoorn (2017) developed a model implemented in the multi-agent simulation framework MATSim which provides dynamic travel assignment where agents optimise their travel plans based on iterative learning from previous experience. The model was designed to reproduce within-day and day-to-day system dynamics using, as an input, a test network based on the road network of Sioux Falls (USA) as well as travel demand and transit supply data. The model was applied to examine the effects of fleet size on passenger waiting times. The results for flexible PT showed that the increase of the fleet size (vehicle capacity) has led to an overall waiting time decrease during the day, which is highly expressed during peak-hours rather than off-peak hours.

Based on the literature review considering the theory and practical application of the agent-based modelling paradigm making it nowadays possible, by taking an advantage of the existing software simulation platforms, to create and represent the examined systems as multi-agent systems composed of interacting agents, the following general conclusions can be drawn:

(i) The urgent need for a simulation framework enabling modelling of complex and dynamic systems consisting of huge numbers of constituents that are in interaction, stimulated scientists and researchers to use the alternative of the conventional simulation modelling approaches. Agent-based modelling appears to be the appropriate and powerful enough approach providing the possibility to model complex systems, representing them as composed of large numbers of autonomous agents interacting with each other within systems’ environments through playing various roles and possessing the ability to learn and adapt.

(ii) However, the practical application of the agent-based modelling paradigm to create agent-based models is accompanied with some inconveniences: (i) agent-based models require significant volumes of data; (ii) the requirements of computational power and speed in terms of computer processors (CPU) and computer memory (RAM) are higher; (iii) there may be some difficulties in the validation of agent-based models in those cases when they are used to model the dynamics of new or unexplored systems.

(iii) Fortunately, the tremendous progress in information and computer technologies during the last more than two decades revealed great opportunities. In order to design, model, explore and analyse a given observed system, in addition to the conventional computer programming languages, there exists a large variety of open-source and proprietary software agent-based modelling platforms, packages and tools, providing ‘rich’ in terms of their functionality software libraries, graphical tools and visualization tools enabling post-simulation analyses, some of which can be extended in accordance with users’ goals and vision;
(iv) The agent-based modelling approach, coupled with the extensible possibilities of the existing software agent-based modelling platforms, packages and tools, reveals new opportunities for academy and practitioners, providing them with powerful functionalities enabling to develop multi-agent models of the observed systems, simulate systems’ dynamics, examine and analyse the obtained results, and establish as a result a sound control over these complex systems that the public transport networks are.

(v) The results obtained through the application of the continuously developing software agent-based modelling platforms for the purposes of a large number research works in different areas, including public transport domain, describing their advantages and strengths in modelling, simulation and analysis of complex systems, are promising.

(vi) The future efforts of PT planners and researchers in this direction should be focused on the application of the agent-based modelling approach for developing a PT multi-agent system providing the possibility to synchronise timetables of PT on a strategic level and on a tactics level to deploy operational tactics by performing fast, real-time simulations within which the main interacting actors will be passenger agents, vehicle agents, road segments and authorities, which however is an object of further studies and modelling.

6.3 Case study

The subject of examination of this case study carried out in Auckland, New Zealand, is a concept for designed-from-scratch monorail25 public transport network with operating straddle-type monorail trains (Ishikawa, Ohazama, Sora, & Sekitani, 1999) servicing the routes of the monorail lines within a MAS with interacting agents, such as PT users (passengers), vehicles (driverless monorail trains) and route sections (monorail tracks).

The stages this case study comprises are described in detail in the following sections:

6.3.1 Generating a network with topology and features of small-world networks

In order to generate a network exhibiting features of small-world networks, the software product for large-scale network analyses, Pajek, was utilised. The following input parameters were used:

- Number of vertices: 9. The intent was to design a monorail network with 9 stations, some of which play the role of hubs (connection/transfer point between routes) and others are simply regular stations (terminal or intermediate) along the route. It is common in small-world networks that as a result of the rewiring of a large number of edges, there might be some disconnected nodes. That is why, for the purposes of this study, the generated small-world-like network without unreachable

25 https://en.wikipedia.org/wiki/Monorail
pairs of nodes has been chosen, i.e. a network having at least one connection to each of the vertices (stops), thus ensuring that all the PT stops will be serviced by a route going through them.

- Number of neighbouring links on each side of a vertex: 1. This value means that in the initial network each vertex is connected to its $k = 2$ nearest neighbours (vertices) on its both sides – left and right.

- Replacement probability also known as rewiring/adding probability (De Nooy, Mrvar, & Batagelj, 2011). It takes values falling in the range $(0,1)$ which in Pajek is implemented with the range of values between 0.00001 and 0.99999. The replacement probability, $p = 0.333$, that was chosen, is the probability with which each edge in the generated network is rewired. This means that each edge is picked up with probability $p$, then it is disconnected from the pair of nodes it is connected to and is then connected to another randomly selected node in the network. In other words, $p = 0.333$ means that approximately 33.3% of all the edges will be redirected through the random rewiring procedure of Watts and Strogatz (1998) illustrated in Chapter 2 (Fig. 2.1).

As a result of the random edge rewiring, the generated network gets transformed from an initial regular network also known as a regular lattice (Fig. 6.2a) with average node degree $\text{AND} = 2.0$ and average network shortest path length $\text{APL} = 2.5$ sections to a small-world network (Fig. 6.2b) with $\text{AND} = 2.0$ and $\text{APL} = 2.444$. On the one hand the latter is highly clustered like a regular lattice and on the other hand, it is characterised with a small network’s average shortest path length (APL) between nodes (i.e. PT stations) – a feature specific to random networks. The diameter, expressing the longest shortest path in the generated network (Fig. 6.2.b), is from vertex 3 to vertex 4 with a total length of 5 edges (sections). Due to the small number of nodes and edges, the generated network is a very rough approximation of a small-world network – a weakness which for the purposes of this study, whose idea is introducing a monorail public transport system, can be ignored. The results of the rewiring procedure would be more precise in larger networks having more than 1000 vertices and edges.

In case the replacement probability used increases up to $p = 0.99999$ when the SWN is mostly random (almost all edges are randomly rewired) rather than structured (like a regular network/lattice with $p \approx 0$), a possible measure for reducing the APL (if needed) would be to increase the number of $k$-nearest neighbours of a vertex from 1 to 2, 3 at the cost of more edges (routes).
After a network which exhibits characteristics of small-world networks was generated, it had to be adapted within Auckland’s urban plan in compliance with existing road and traffic conditions as well as environmental restrictions, such as streets, residential and business buildings, and others. By using Google Maps\(^{26}\), the above has been made so that the nodes of the network could serve as stations of the prospective monorail PTN placed at strategic locations (main city areas, central business district area, university campus, hospital, etc.) and serving as hubs having the potential to generate and attract trips. The adapted structure within Auckland’s environment network’s structure composed of nodes (PT stations) and connecting sections (along the PT lines) is shown in Fig. 6.3.

\(^{26}\)https://www.google.com/maps
The advantage of designing a small-world-like network structure, compared to other PTNs, most of which in terms of their structure resemble random networks, is that the generated network would have the shortest APL as is the case in random networks (i.e. globally efficient), but at the same time would also be more highly-clustered than a random network (i.e. high local efficiency). In other words, in large PTNs distances between stops, expressed as number of sections (along routes), could significantly increase. A small-world network solves this problem by ensuring (as a result of the rewiring procedure) that the PT stops would be reachable in a small number of hops (route sections in our example). And the small-world-like network would connect these stops with a smaller number of route sections compared to regular networks and would still provide better connection between local PT stations (as it is highly clustered as already mentioned) compared to random graphs so that there will be no disconnected stops left.
6.3.3 Design of an initial route network

This section briefly explains how a monorail public transport network was designed composed of three lines serviced by routes that go through the generated and subsequently adapted for Auckland’s urban conditions small-world-like network discussed in the previous section 6.3.2.

The initial structure of the adapted network was designed by using the Java Open Street Map (JOSM) network editor\(^{27,28,29,30}\), a free software which, due to its functionality and Plug-Ins enabling users quickly and relatively easily to design and extend different networks, has become a very popular and widely used tool.

There is a MATSim Plug-In available (Neumann & Zilske, 2016) which easily integrates with JOSM, thus providing users with the opportunity to take advantage of both JOSM's and the Plug-In's functionality. The MATSim Plug-In simplifies and speeds up the process of creating, exporting, subsequently importing for editing (if it is needed) MATSim networks.

The number of lines in the monorail network and their routes that have been chosen to service all stations without visiting each station more than once, is 3. Those created within JOSM’s working environment and by using the MATSim Plug-In network consisting of three lines/routes with a total length of 9.1 km is shown in Fig. 6.4 and the separate lines (Line 1, Line 2 and Line 3) having lengths of 2.55 km, 2.45 km and 4.1 km, respectively, are shown in blue in Figs. 6.5a to 6.5c. For simplicity, the route network was designed so that through each section goes only one route.

Since in MATSim links are uni-directional, where a road (or railway track as in our case) is passed by vehicles in both directions, parallel routes (sequence of links) – one for each direction – had to be created in JOSM. The network structure created in JOSM was then saved, by using the MATSim Plug-In, in an XML (eXtensible Markup Language\(^{31}\)) file “PtNetwork.xml” which contains data regarding the network elements (nodes and links) ready to be directly opened in MATSim – a matter discussed in the next section in this chapter.

\(^{27}\) https://josm.openstreetmap.de/
\(^{28}\) https://josm.openstreetmap.de/wiki/Introduction
\(^{29}\) https://wiki.openstreetmap.org/wiki/JOSM
\(^{30}\) https://wiki.openstreetmap.org/wiki/JOSM/Guide
\(^{31}\) https://en.wikipedia.org/wiki/XML
Figure 6.4. Illustration of the structure of the designed prospective monorail public transport network

Figure 6.5. Lines within the designed monorail PTN: (a) Line 1, (b) Line 2 and (c) Line 3
Multi-agent simulation of the passenger transportation process within a monorail public-transport network serviced by autonomous trains

That designed within the JOSM editor and exported to an “PtNetwork.xml” file network served as a fundamental part in the proposed multi-agent system composed of the interacting agent, such as PT users (passengers), vehicles (autonomous monorail trains) and route sections (monorail tracks). The implementation of the designed MAS and the simulation of the passenger transportation process were performed within the working environment of the free, open-source, Java-based, agent-based platform MATSim\textsuperscript{32} enabling implementation of a large-scale multi-agent transport simulation. In this regard, the following preparation work was involved:

- Configuring into a “Config.xml” (Appendix E, section E.1) file values for all the settings and input parameters (transport mode, availability of cars, activity types, duration, number of iterations, start and end time of the simulation) as well as including the names of the files, such as “PtNetwork.xml”, “TransitVehicles.xml”, “TransitSchedule.xml” and “Population.xml” specific for the simulation scenario and containing information regarding network, vehicles, schedule and passengers’ daily plans that will be read and implemented during the simulation. Each of the above files contains the following data:

  - the “PtNetwork.xml” (Appendix E, section E.2) file contains data regarding the network elements – nodes (id, and x and y coordinates) and links (id, nodes the link connects, length, free speed, lane capacity, lanes, direction and transport modes). The structure of the designed network consists of 100 links in total and 106 nodes, i.e. 53 nodes in each direction (Fig. 6.6). The visualisation of the input data (route network, transport mode (trains), and passengers as well as the simulation output results (including the actions performed during the simulations that have been recorded as events in the file of events) was done by using Via\textsuperscript{33}, version 1.8.2 – a visualisation tool enabling to extract and visualize data, represent and record the simulation, and perform post-simulation analyses. It is worth mentioning for clarity that these 106 nodes, which mainly serve to join the edges of the network in straight and curved sections, do not correspond to the 9 monorail stations. A scheme of the created monorail public transport network (sequence of stations and connecting sections) serviced by routes going along 3 PT lines (Line 1: 2-3-7-8, Line 2: 1-4-3, and Line 3: 9-6-5-7-4) is shown in Fig. 6.7.

\textsuperscript{32}https://matsim.org/
\textsuperscript{33}https://www.simunto.com/via/
\textsuperscript{34}https://www.simunto.com/data/via-1.8.2/via-manual.pdf
the “TransitVehicles.xml” (Appendix E, section E.3) file contains data about vehicle type, transport mode description, vehicle capacity (seats and standing room), vehicle length as well as a unique vehicle id assigned to each vehicle which is subsequently used into the transit schedule of the separate lines. As for the purposes of the presented case study there are no additionally developed (to those in MATSim) and integrated into the multi-agent simulation features that would have made vehicles (monorail trains) behave as autonomous, it is only assumed in this work that they are such, i.e. monorail trains are considered self-driven or alternatively, they could be driven remotely (e.g. by an operator from a controlling dispatch centre).

the “TransitSchedule.xml” (Appendix E, section E.4) file is where the PT stops are defined through their unique id number, x and y coordinates, name (optional) and network link id each PT stop belongs to. In this file each PT line is declared with its id (name), transit route name servicing the line in right and opposite direction as well as the transport mode (train). Each line’s route is defined as a sequence of links each vehicle visits while travelling from the first to the last station as well as a route profile showing the sequence of stops the vehicles (trains) stop at while travelling along the route of the monorail line. Each stop id is accompanied by an arrival time offset (the time elapsed after the vehicle has left the first stop of the route), departure time as well as a flag designating if the vehicle should wait at the stop in case it has arrived earlier than expected (when it is going ahead schedule). It is important to mention that in this file, there is also data regarding vehicle departures which is written in the “departures” section. Each departure is defined by means of an id, vehicle reference id (for each of the directions) and departure time from the terminal station.

the “Population.xml” (Appendix E, section E.5) stores information about the agents and their daily plans. In other words, each agent (person) has a daily plan. Each plan contains a list and actual location of activities (home, work, study, shop) representing the actions an agent is planning to do on a daily basis. The activity types are defined with x and y coordinates and links (optional) showing from where an activity can be reached. Activities also have an ending time. The implementation of each activity requires trips (legs). Each leg requires only one mode. Legs can be done by walking or by using the available transport modes. Therefore, each leg needs to have a transport mode assigned to it. A simple daily plan would be the following: a person with id = 1 may have a daily plan comprising the activities home-work-home which are implemented by making trips (legs) with the available modes of transport between each pair of activities. For additional information considering setting up of a simulation scenario or to access other related literature, readers may refer to the official MATSim website https://matsim.org.
The behaviour of the modelled MAS and the interaction between the agents in it were simulated throughout a whole day between the hours 07:00 and 18:00 with trains operating during the morning peak-hour (07:15-08:15) and within the afternoon peak-hour (between 17:00 and 18:00) with 15-minute intervals. The multi-agent simulation experiments were carried out using MATSim, version matsim-0.10.0, released on 25.08.2018. The timetable ("TransitSchedule.xml" file) was designed so that during peak hours there are vehicles running in the opposite directions along the routes of each of the three operating monorail lines. To establish control on the proposed monorail PTN resulting in avoiding walk legs (usually caused by the lack of a service at stops) and facilitating passengers in transferring from one route to another at connection points, the schedule of the trains servicing the separate lines was manually adjusted.

*Figure 6.6. Visualisation within Via of the designed by using JOSM network represented by nodes and connecting links*
The in-vehicle travel times between the stations along each of the three monorail lines, shown in Tables 6.1 to 6.3, were calculated based on the distances measured within Google maps between the stations (section lengths) and the adopted average travel speed. The calculated travel times were then used in creating the train timetables with 30-second stays of trains at stations. The following technical and operational characteristics for the assumed autonomous vehicles (trains) operating within the double-tracked monorail network were used:

- length of monorail trains: 10 m.
- train capacity: 45 passengers (15 seats plus room for 30 more standing persons).
- average travel speed: 36 km/h;
- vehicle headway: 15 min;
- vehicle frequency: 4 monorail trains going in both directions of the routes servicing each of the three monorail lines during the morning peak-hour and 4 more train in direction during the afternoon peak-hour (Appendix F, Figs. F.1 to F.6);
- train id – a sequential number. For example, an uneven id number (e.g. 101) is chosen for trains going in the right direction and even numbers (e.g. 102) for trains running in the opposite direction along the monorail line.
Table 6.1. Monorail stations, sections’ lengths and calculated in-vehicle travel times between the stations along the route servicing monorail line # 1

<table>
<thead>
<tr>
<th>Seq. No</th>
<th>i</th>
<th>j</th>
<th>Section</th>
<th>Length, L, m</th>
<th>Average in-vehicle travel time, T, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2-3</td>
<td>860</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>7</td>
<td>3-7</td>
<td>1090</td>
<td>109</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>8</td>
<td>7-8</td>
<td>600</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2550</strong></td>
<td><strong>255</strong></td>
</tr>
</tbody>
</table>

Table 6.2. Monorail stations, sections’ lengths and calculated in-vehicle travel times between the stations along the route servicing monorail line # 2

<table>
<thead>
<tr>
<th>Seq. No</th>
<th>i</th>
<th>j</th>
<th>Section</th>
<th>Length, L, m</th>
<th>Average in-vehicle travel time, T, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>4</td>
<td>3-4</td>
<td>1100</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
<td>4-1</td>
<td>1350</td>
<td>135</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>2450</strong></td>
<td><strong>245</strong></td>
</tr>
</tbody>
</table>

Table 6.3. Monorail stations, sections’ lengths and calculated in-vehicle travel times between the stations along the route servicing monorail line # 3

<table>
<thead>
<tr>
<th>Seq. No</th>
<th>i</th>
<th>j</th>
<th>Section</th>
<th>Length, L, m</th>
<th>Average in-vehicle travel time, T, seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>6</td>
<td>9-6</td>
<td>900</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>5</td>
<td>6-5</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>7</td>
<td>5-7</td>
<td>1500</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>4</td>
<td>7-4</td>
<td>1300</td>
<td>130</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>4100</strong></td>
<td><strong>410</strong></td>
</tr>
</tbody>
</table>

Due to a lack of recent actual data regarding passenger trips and activities, the simulations were performed under the following assumptions:

- it is assumed that most of work and study facilities are located in the CBD and the surrounding suburbs.
- the initial users of the monorail PT system would be the 250 created agents (synthetic population) with their daily plans consisting of activities and trips. It is also assumed that the number of passengers is initially small because the monorail service has just started functioning and there are not many passengers who have chosen it as an alternative trip mode, and the operator is still experimenting with the fleet size and frequency of service.
- the data in the origin-destination matrix in Table 6.4 represents the demand for trips between the monorail stations of the above synthetic 250 agents.
- station 7 only plays the role of a transfer hub without any trips originating from or destined to this station except for the trips requiring transfer for which passengers get off the train servicing one line to get on the train servicing another.
Table 6.4. PT O-D travel demand matrix

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0</td>
<td>30</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td></td>
<td>0</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>18</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>88</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>35</td>
<td>0</td>
<td></td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>12</td>
<td>20</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>47</td>
<td>88</td>
<td>150</td>
<td>10</td>
<td>18</td>
<td>0</td>
<td>82</td>
<td>60</td>
<td>500</td>
</tr>
</tbody>
</table>

6.3.5 Discussion of results

The simulation output results showed that for accomplishing/implementing their daily plans, the 250 agents have done 1992 legs (trips) in total, 746 of which (37.5%) are the PT legs with trains and the rest 1246 are walk legs (62.5%). This result reveals that in order to implement their plans each one of these passengers has made approximately three trips on average (746 trips divided by 250 agents) using for this purpose the proposed monorail public transport as a mode.

In order to observe the dynamics of the modelled system, let us consider in a sequential order a couple of screenshots representing the PT operations along the monorail network during the simulation within the morning peak hour.

As soon as the simulation starts, passengers at the terminal stations get on the departure trains: 15 passengers in the train going from station 1 to station 4 along line 2 (as shown in Fig. 6.8), 10 passengers in the train traveling from station 4 to station 7 along line 3, 45 passengers travelling in the train going along line 1 from station 2 to station 3 utilising 100% of vehicle capacity and 45 more passengers who started their trip at station 9 and are travelling along line 3.
As can be seen in Fig. 6.9, in accordance with the O-D travel demand data in Table 6.4, those 15 passengers travelling to stations 4 from 1 alighted the train at this station as did 15 of the 45 passengers travelling in the train along line 1 and alighted the vehicle at station 3. The vehicle with the remaining 30 passengers on board continued going along line 1 in direction station 7.
It is shown in Fig. 6.10 that all 10 passengers travelling along line 3 to station 5 have alighted the train at this station. In addition, this figure also shows that 18 out of 30 passengers who were travelling in the train along line 1 alighted the train at station 7 to make a transfer, and the other 12 continued their trip destined to station 8.

![Diagram of passenger transportation process](image)

**Figure 6.10. Screenshot 3 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:20:19**

As the simulation goes on (Fig. 6.11), 20 out of 45 passengers who were travelling in the train along line 3 in direction 9-4 have left the vehicle at station 7 to await their connection. The other 25 passengers continued their trip to station 4.

The blue circles around the PT stations represent the agents (passengers) who have reached the destination point of their planned trip to implement their activities.

Each of the three monorail lines (line 1, line 2 and line 3) is serviced by one route going in two directions – right and opposite – as shown in Table 6.5 below.

Depending on the number of lines going through each of the fore-mentioned nine monorail stations (shown throughout Figs. 6.7 to 6.11) and the routes servicing them, each station has corresponding unique stop Ids (Table 6.6) used in MATSim to create public transit stops and build route profiles.
Figure 6.11. Screenshot 4 of the multi-agent simulation of the passenger transportation process along the lines of the proposed monorail PTN for Auckland taken at 07:21:17

Table 6.5. Routes along the monorail PT Lines in each of the directions

<table>
<thead>
<tr>
<th>Monorail line No.</th>
<th>Route name*</th>
<th>Opposite direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>s1r1TOs1r4</td>
<td>s1o1TOs1o4</td>
</tr>
<tr>
<td>Line 2</td>
<td>s2r1TOs2r3</td>
<td>s2o1TOs2o3</td>
</tr>
<tr>
<td>Line 3</td>
<td>s3r1TOs3r5</td>
<td>s3o1TOs3o5</td>
</tr>
</tbody>
</table>

* The meaning of the bolded letters and numbers in the route s1r1TOs1r4 is as follows:
s1r4 – stop along route 1, in right direction, with a sequential number 4.
In other words, monorail Line 1 is serviced in right direction by route s1r1TOs1r4 going from stop s1r1 to stop s1r4.

Table 6.6. Correspondence between the monorail PT stop/station numbers and the PT stop Ids in the MATSim’s PT routes

<table>
<thead>
<tr>
<th>Monorail stop/station No.</th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s1r1TOs1r4</td>
<td>s2r1TOs2r3</td>
<td>s3r1TOs3r5</td>
</tr>
<tr>
<td>1</td>
<td>---</td>
<td>s2r3</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>s1r1</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3</td>
<td>s1r2</td>
<td>s2r1</td>
<td>s3r5</td>
</tr>
<tr>
<td>4</td>
<td>---</td>
<td>s2r2</td>
<td>s3r3</td>
</tr>
<tr>
<td>5</td>
<td>---</td>
<td>---</td>
<td>s3r2</td>
</tr>
<tr>
<td>6</td>
<td>s1r3</td>
<td>---</td>
<td>s3r4</td>
</tr>
<tr>
<td>7</td>
<td>s1r4</td>
<td>---</td>
<td>s3o4</td>
</tr>
<tr>
<td>8</td>
<td>s1o1</td>
<td>---</td>
<td>s3o2</td>
</tr>
<tr>
<td>9</td>
<td>---</td>
<td>---</td>
<td>s3r1</td>
</tr>
</tbody>
</table>
The output results of the performed multi-agent simulations of the passenger transportation process in both the directions (right and opposite) for each of the three lines within the designed monorail public transport network representing data regarding the route-time diagram (the graphical representation of the train timetable), passengers entering/leaving the stations, train loads in the sections between each two stations, passenger trips between the stations of routes as well as data related to transfers made between the lines at connection points (hubs) are shown in a sequence throughout Figs. F.1 to F.26 and Tables F.1 to F.2 in Appendix F.

Vehicle load data could be used as a starting point in planning the fleet size and frequency of service throughout the day on the separate monorail lines. The number of trips between the stations and station loads could take place in identifying the most loaded (important) stations, finding the rationale of temporal “closure” or opening of stations applying for this purpose a skip-stop operation (Ceder, 2007). The number of transferring passengers at connecting stations could be considered in setting up frequency of service and timetable synchronization of the vehicles operating along the different lines within the monorail system as well as in improving the coordination between the available PT modes within an integrated multimodal PT network, which would allow them to serve these passengers on a timely manner.

In support of the above, the obtained multi-agent simulation output results regarding the passenger transportation process along the routes servicing line 1 in both the directions were examined and analysed as follows: Fig. 6.12 shows that the first train (in red) leaves the first station s1r1 at 07:15 fully (100%) loaded. When this train leaves the second station (s1r2) along the route, it continues in direction station s1r3 67% full carrying 30 passengers. Once the train has left the third station (s1r3) it travels until it reaches the last station (s1r4) with only 12 passengers on board who have occupied approximately 27% of its capacity. Due to the low passenger demand, when the second train (in dark blue) leaves the first station at 07:30, there are only two passengers in it who get off the train at the next station. It is obvious that the other two trains of the schedule (those departing the first stop at 07:45 and 08:00, respectively) are travelling along the route empty, which gives an indication that the operator of the monorail PT system could operate during morning peak-hour in the right direction (from s1r1 to s1r4) with one train having a larger size instead of two small train. In the meantime, the operator can also take out from the schedule the 3rd train and the 4th train which otherwise would be going empty.
From Fig. 6.13 below, which represents the utilization of the trains going in the opposite direction (from s1o1 to s1o4), can be seen that the first train (in violet), which according to the timetable departs the first station (s1o1) at 07:20, is going fully loaded along the first two route sections (between the stops s1o1 and s1o3) with 45 passengers travelling in it. As all the passengers alighted from the train at stop s1o3 and no passengers boarded the vehicle, the train is going to the last station (s1o4) empty. In contrast to the first train, the second one (in dark blue) leaves stop s1o1 at 07:35 with utilized vehicle capacity slightly above 50% (25 passengers). When the train leaves station s1o2, similar to the previous train, it is fully occupied. And again, since all the passengers get off the train at station s1o3 and no passengers get on the vehicle at this station, the train travels empty and there are no passenger trips between this station (s1o3) and the last station (s1o4), which can be seen in Figs. 6.14 to 6.15 showing the passengers carried between the stations along the route by the first train (departing at 07:20) and the second train (departing at 07:35), respectively. Similar to the trains in the right direction servicing the same line, the last two trains, departing at 07:50 and 08:05 are travelling empty and therefore due to the low demand could be cut from the schedule in the morning hours.

**Figure 6.12. Train loads along route s1r1TOs1r4 servicing monorail Line 1 in right direction**
Figure 6.13. Train loads along route s1o1Tos1o4 servicing monorail Line 1 in opposite direction

Figure 6.14. Passengers carried between the stops along route s1o1Tos1o4 servicing monorail Line 1 in opposite direction by the train departing station s1o1 at 07:20
The above example demonstrated how the visualized simulation output results can be used in performing a post-simulation analysis which helps to identify:

- To what extent the train capacity is used along the routes within the monorail network;
- Whether or not the provided fleet size (vehicle capacity) and number (frequency of service) is enough to meet the existing passenger demand and what measures should be taken in response. For instance, taking out trains from the schedule, increasing the capacity of the operating trains by adding additional wagons (cabins) or replacing them with monorail trains providing larger capacity.

In regards to the transfers made by the passengers within the monorail route network during the simulated times, the following can be noted: The fact that there are no transfers made at stop 4 can be explained with the O-D matrix (Table 6.4) according to which all the trips that have stop 1 as an origin or a destination point go to or come from stop numbers 3 and 4. The latter are serviced by the routes going along line 2 which also service and stop 1. In other words, PT users make trips between the stops 1, 2 and 3 by using direct route which excludes the need to make transfers.

The simulation output results, especially those regarding the daily person plans implemented without extra PT trips or walk legs that have replaced the planned PT legs, indicate that the system’s functioning has been satisfactorily reproduced when modelling it as a MAS. This reveals the potential of designing and implementing a monorail PTN as an alternative or supplementary (feeder) to the main bus PTN in Auckland. As demonstrated above, post-simulation analysis of the results could be performed to explore and further improve the system’s performance, which opens the door for a follow-up research work including elaborating and experimenting new simulation scenarios.
CHAPTER 7. CONCLUSIONS

The merits of this doctoral thesis and the contributions it brings to the transportation engineering research field can be summarised in the following main conclusions:

Chapters 2 and 3:

The novel method developed, which combines public transport theory and network science tools with the practical application of computer programming, large network and statistical data analyses enables examination of the structure and topological features of complex public transport networks of different PT modes – buses, metro and subway, which in turn allows evaluation of network efficiency and identification structure weaknesses.

The method proposed, in its last steps, allows not only introduction of new PT performance measures and indicators, but also solutions of operational tasks which could find application in PT operations: (i) given the desired average route length to determine the proportion of the origin-destination PT demand that can use direct routes without transfers and the share of the trips requiring transfers, and (ii) given the proportion and amount of the origin-destination PT demand requiring transfers to determine the required average route length.

The empirical contributions – statistical relationships (regression models) derived as well as the PT network types established, and topological characteristics revealed as a result of the application of the method on real-world case studies – could be helpful to practitioners in taking decisions aimed at re-structuring existing PT networks or designing prospective ones. The analyses performed to examine the efficiency of the studied public transport networks showed how by using network science concepts it is possible to identify and reveal connectivity weaknesses between the nodes in a network, which could be used as a starting point in network reconstruction analyses.

The results attained from the application of the method, which connects complex network science theory and PT operation planning, open the door for further research work directed to examining vulnerability and faults tolerance of complex PT networks characterised with different topologies as well as redesigning PT route networks and performing network reconstruction analysis.

Chapter 4:

The results obtained from the PT observations as well as from the implementation of the developed simulation model enabling modelling of the interaction of buses, passengers, and cars along a single route as a small-size multi-agent system could be used by practitioners as a tool to model and analyse PT performance measures which in turn would facilitate them in making informed operational decisions along a route within a public transport network.
Chapter 5:

In the light of the large variety of existing simulation models and tools, the newly-created simulation model, implementing the novel concept of autonomous cars, stands due to:

- the small number of input variables, which makes more realistic the chances for the model’s usage and subsequent application.

- its flexibility. Through minor modifications, the model could be relatively easily and quickly adapted for modelling the passenger transportation process along a public transport line characterised with specific parameters: route, vehicles carrying passengers, and variable passenger demand.

- the ability of the model to enable evaluation of the existing system’s performance and efficiency along the route of a PT line under simulation, which would allow PT experts to effectively plan the PT service under different (existing and forecasted) conditions and scenarios.

The proposed simulation model provides the possibility to model the passenger transportation process along a route within a PT network as a high-frequency, metro-like PT service using punctual self-driving vehicles such as buses. The simulation output results showed that:

- the model satisfactorily reproduces the parameters of the modelled system

- through the application of the model an improved and reliable PT service was achieved

The benefits of the application of the simulation model and the autonomous vehicle concept it implements would be twofold:

(i) from a PT user’s perspective – vehicles arriving at bus stops on time resulting in a reliable PT service with significantly reduced passenger waiting times at PT stops and reduced number of unserved passengers

(ii) from a PT operator’s perspective – better vehicle capacity utilisation and possibly reduced operator cost from drivers’ wages, especially in the case of a high frequency service with driverless vehicles

Some of the findings obtained as a result of the application of the simulation model could be taken into account in a further research work – development and application of a model on a real-life case study comprising more than one route in a public-transport network with a specific network topology.
Chapter 6:

The implementation of a monorail PTN with operating autonomous trains is proposed in this thesis as a possible solution for establishing a reliable and punctual PT service which would be faster than the service provided by buses because of its independence from traffic congestion (monorail trains, following the routes they service, will be travelling along an isolated network of straddle-type monorail tracks elevated on monorail beams).

The attained results of the performed multi-agent simulation of the passenger transportation process within the proposed MAS, functioning as an interaction of the agents “passengers”, “driverless monorail trains” and “monorail tracks”, reveal the potential of implementing a monorail PTN. This would open the door for researchers and scientists to new ideas and opportunities in modelling, simulating, exploring and analysing public transit systems by combining network science and public transport modelling methods, approaches and tools.

In contrast to other models, including the models presented in the earlier chapters of this doctoral dissertation, the proposed multi-agent monorail PT system enables modelling and simulation by using MATSim, the passenger transportation process across a whole network. This would allow PT planners to “view” and manage the whole network composed of more than one route and not a separate, single route considered in isolation from the other routes, thus providing improvements which would not necessarily lead to an overall improvement of the entire PTN.

Although the applied, on a case study, network science – public transit operations approach, combining a generated network with a specific (small-world) topology used as a foundation layer of a newly-designed monorail PTN on the one hand and the performed multi-agent simulations of the passenger transportation process on the other hand, does not make a claim to be detailed enough and exhaustive, it could serve as a basis for an extension of the present research work or for conducting new research in this direction not only taking place in Auckland, but also in other cities across the world.

Regardless of the fact that the proposed monorail system would not be as flexible as a bus route system (in case of an incident the train cannot be re-scheduled to an alternative route or if there is a vehicle failure, the train cannot just be replaced or overtaken by other trains), due to the separation of the lines, any possible breakdown of the system would only locally block the passenger transportation process in the affected, isolated line and the other two lines would still be operating.

In case actual passenger demand data is used, the proposed MAS could be extended and used in performing multi-agent simulation of the passenger transportation process with different size self-driving trains and frequency of service, aimed to provide PT users with a reliable service and offer transit supply capable of covering the variable travel demand. The latter could be the subject of another project, though.
In contrast to conventional bus routes, the proposed monorail public transport system would offer the following main advantages:

- **From a user’s perspective:**
  - given that the monorail trains run on an isolated route network (elevated tracks on monorail beams), the monorail system would offer prospective users a safer (no crashes with other vehicles) and faster service (it does not have conflict points with the other transport modes as they operate at different levels);

- **From a transport operator’s and authorities’ perspective:**
  - the construction of a monorail system requires less land which nowadays in crowded and heavily built modern towns would be a huge advantage. This case study neither considers nor takes into account the fact that elevated railway systems, which is what the monorail systems are, are extremely expensive and require significant initial investment for building the infrastructure of an entirely new monorail public transport system – an important matter that could be a subject of separate research which is beyond the scope of this thesis.
  - since the designed monorail PTN would operate with autonomous trains, this on the one hand would save cost incurred for paying drivers’ wages and on the other hand, it would eliminate the risk of mistakes caused by the human factor (as the trains would be controlled remotely).

- **From a society point of view:**
  - a possible design and implementation of a monorail public transport system in Auckland, having the potential to replace buses in some central areas and supplement them in others, would partially alleviate the vehicular traffic in the central business district of Auckland;
  - monorail trains do not pollute the environment with emissions.
7.1 Summary of the main findings, results and conclusions

The main findings, the results attained, and the conclusions drawn in each of the chapters in the thesis are summarised in Table 7.1 below.

<table>
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<tr>
<th>Chapter #</th>
<th>Task</th>
<th>Findings, results and conclusions</th>
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| 2 & 3     | Conducting a literature review of research works related to examining and analysing complex networks, including public-transport networks. | The literature review conducted, encompassing fundamental and recent research in the domain of network science, spatial networks, complex networks, transport geography, and public transport in particular, enabled drawing the following main conclusions:  
- The limitation of the existing approaches and tools for analyzing real-life complex networks, such PTNs, place a number of new challenges for researchers and scholars in terms of the data required, methods to be applied, and software to be used;  
- Through combining recent findings of other fields of research, NS enables exploring, examining, analyzing, modelling and simulating real-life complex networks;  
- Theories related to NS and the findings of complex systems are a good foundation for practical studies of the structure of real-world networks (including PTNs) through an evaluation of topological properties such as CC, APL, NDD and network efficiency (local and global). |
| 2         | Developing a novel and efficient method, coupled with a software tool, allowing automated extraction and processing of data, which enables examining and analysing the structure and the topological properties of Public-transport networks (PTNs) and evaluate networks’ efficiency. | The novel method developed provides the possibility not only of examining existing PT networks for scale-free characteristics and revealing the presence of hubs (which is important particularly for scale-free networks, as although these networks are robust against random, i.e., accidental failures, they are highly vulnerable to targeted or coordinated “attacks”), but also of exploring network topology and discovering “small-world” features and evaluating network’s efficiency – local and global – considered from networks science’s point of view.  
This method, after a condition regarding the GTFS text files’ formatting is met, could be applied to extract and process updated GTFS data “feeds”, including updated or newly created timetables put into operation reflecting changes in routes during the year.  
The examined bus-route network is neither a scale-free nor does it exhibit all the features of “small-world” networks. Instead, it can be considered as a mixture of exponential and scale-free networks, which means that the evolution of the bus-route network in Auckland is a consequence of random rather than preferential attachment of newly opened stops.  
The empirical contributions of this work are threefold:  
(i) The probability node-degree distributions, the regression equations empirically derived and the values of the PT topological characteristics could be used by practitioners when making decisions about re-structuring existing PT networks or designing prospective ones.  
(ii) The developed software program automates and speeds up the process of extraction and processing of GTFS data of large-scale PT networks thus providing the data in a format ready for further analysis and examination of the topological properties of complex PT networks.  
(iii) The method, in its last step, enables not only to introduce new PT performance measures and indicators, but also to solve two operational tasks used in practice: (a) given the desired average route length to determine the proportion of the origin-destination (O-D) PT demand that can use direct routes without transfers and the share of trips requiring transfers, and (b) given the proportion, and amount, of the O-D PT demand requiring transfers to determine the required average route length. |
| 3         | Extending the developed method utilising Network science (NS) concepts and tools and applying the proposed method on real-life case studies with the purpose to explore the structure of PTNs, analyse networks’ topological properties, evaluate the efficiency of the studied networks and outline directions for network’s improvement on a route and network level. | The network analysis performed in exploring the topological properties of the Washington DC’s and the Oslo’s metro networks showed that when represented in an L-space network topology, the networks examined do not exhibit small-world properties, and hence, they are not small-world networks.  
The examination of the Washington DC’s metro network and its analyses also showed that the network is neither a scale-free nor random network; this is based on the consideration of network’s node degree distribution, the number of the metro lines servicing each station and representing the network as a bus station network. In contrast to the Oslo’s metro network, the metro network in Washington appears to be a complex network.  
The analysis considering the networks’ global efficiency, performed by using network science concepts and findings, showed that both the metro networks examined have low valued global network’s efficiencies and therefore appear not to be faults tolerant. In case of a railway section’s breakdown, this would significantly affect the quality of the transport service provided, because of the lack of alternative connections linking the disconnected metro stations. These results illustrate connectivity weaknesses, thus indicating that there is a room for improving the connectivity between the stations within the networks. |
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<th>Chapter #</th>
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<td>4</td>
<td>Reviewing books, research works such as scientific articles, papers, and reports devoted to Agent-based modeling and simulation as well as works covering the concept of Multi-agent systems and their application in various research fields and in the area of PT in particular.</td>
<td>Based on this review of the literature, three main conclusions can be drawn: - in order that the simulation model be able to produce realistic and reliable results, in modelling a PT system as a MAS, other transport modes, such as private cars, taxis and bicycles should be considered; - both MAS and ABMS are useful and well suited to modeling and simulating PTN in a relevant way; Some researchers have designed their own MAS to solve particular tasks (Balbo &amp; Pinson, 2001; Zhao, Bukkapatnam, &amp; Dessouky, 2003). Others, in order to deal with several problems related to PT, developed general MAS frameworks for PT system modelling and simulation (Kieser, 2010; Nguyen, Bouju, &amp; Estraillet, 2012; Meigman, Simonin, &amp; Koukam, 2007; Wahba &amp; Shalaby, 2006; Li, Zhang, Wang, Lu, &amp; Mu, 2011). There are also some researchers (Kichhöfer, Kaddoura, Neumann, &amp; Tirachini, 2012; Kaddoura, Kichhöfer, Neumann, &amp; Tirachini, 2015a) who use one of these frameworks to address their own objectives; - in order to model an existing PTN or one of its routes, a suitable software product applying the ABMS approach, should be chosen to enable modeling of PT as a MAS and allowing for performing simulations and further exploring the system modeled.</td>
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<td>4</td>
<td>Observing a route of operating public-transport line on a real-life case study, processing data obtained from direct observations revealing actual bus loads, and evaluation of vehicles’ capacity utilization.</td>
<td>It was found that on the average 89% of the theoretical vehicle capacity is used. The difference between the theoretical and observed bus capacity results from the fact that standing passengers do not go to the far rear of the bus, which allows bus drivers see people next to them think that the bus is fully loaded, which is inaccurate because in effect there is still space available at the rear part of the vehicle.</td>
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<td>5</td>
<td>Modeling and simulation of the passenger transportation process along the examined PT line as a Multi-agent system (MAS) composed of interacting agents such as bus drivers, buses, cars and passengers. Analysing the behaviour of the modeled system under different simulation scenarios with the purpose to identify the best combination of vehicle passenger capacity and frequency of service.</td>
<td>The proposed simulation model calibrated and validated for Auckland’s PT bus line provides a helpful tool enabling modelers and planners to perform simulations by which the modeled system can be observed, its performance measures analysed, and reasonable operational decisions made. The simulation output results have demonstrated that when PT demand is less than bus capacity, that capacity does not affect the average waiting time at bus stops. In cases where PT demand is high, not surprisingly, the high bus capacity, resulting in an increased number of passengers boarding the bus, indirectly causes increased passenger waiting times, unless the frequency of service is increased. These results could serve PT operators well in the trade-off situation when choosing between increased bus frequencies and larger size bus capacities, especially when the PT demand at bus stops is high.</td>
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<td>5</td>
<td>Performing a review of literature sources discussing simulation modeling and its practical application at public-transport operations.</td>
<td>The literature review, comprising various model types, allows us to conclude that regardless of the strengths and the advantages of the models, their practical application is accompanied by some difficulties that can be summarised as follows: • some models are unnecessarily complex to use and/or include a large number of input variables in them. This makes it hard to find data to feed these models, which makes it difficult to apply them in practice without using specialized computing software and tools; • some models are developed with specialized software products, which is limiting because: some of these products are expensive to attain, others require programming skills, and for part of the rest it takes a long time to learn and build even relatively simple models. As a whole, the above makes the software hard to use for building and implementing more complex models; • simplified models that do not describe the system in detail do not give accurate results; • due to the specifics of the areas for which the models have been developed (such as town architecture, road infrastructure, route characteristics), some models are only applicable to these areas and transport conditions, which means they are not universal and therefore cannot be directly applied or easily reworked and adapted in different case studies; • “static” models used in modelling a limited number of stop along the route are not flexible as they cannot be adapted for another PT line. Based on the conducted literature review it was concluded that one of the ways to improve transit service reliability is, on the one hand, to decrease one of its measures – average passenger waiting time at stops – by increasing the frequency of service of autonomous vehicles running along the route (which would cut costs for wages) and, on the other hand, by providing exclusive (separated) lanes that would reduce to a minimum the headway’s deviation, thus avoiding the impact of delays on travel times between stops incurred on signalised intersections and along the road due to traffic congestion.</td>
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In light of the rich variety of simulation models and tools, this simulation model stands out because of:
- the small number of input variables, which makes the model’s usage and subsequent application realistic;
- its flexibility, which enables, through minor modifications, relatively easily and quickly reworking the model and thus adapting it for modelling the passenger transportation process along a public-transport line characterised with specific parameters with regard to the route, the vehicles carrying passengers, and the variability of passenger demand;
- the ability of the model to enable evaluating the existing system’s performance and efficiency along the route of a PT line under simulation, which would allow PT planners to effectively plan the PT service under different (existing and forecasted) conditions and scenarios.

The newly-created simulation model, implementing the novel concept of autonomous cars, provides the possibility to model passenger transportation process along a route within PT network as a high-frequency, metro-like PT service using punctual self-driving vehicles such as buses. The simulation output results showed that: (i) the model satisfactorily reproduces the parameters of the modelled system and (ii) through the application of the model an improved and reliable PT service was achieved.

The benefits of the application of the simulation model and the autonomous vehicle concept it implements would be twofold: (i) from PT users’ perspective – vehicles arriving at bus stops on time resulting in a reliable PT service with significantly reduced passengers waiting times at PT stops and reduced number of unserved passengers and (ii) from PT operators’ perspective – better vehicle capacity utilization and possibly reduced operator’s cost from drivers’ wages especially in the case of a high frequency service with driverless vehicles.

The results from the simulation scenarios showed that the model satisfactorily reproduces the parameters of the system modelled, which allows us to summarise the simulation output results as follows:
- Among the scenarios, scenario 4 simulating a high frequency, metro-like PT service, due to the small vehicle headways, provides passengers with the least average waiting time at bus stops;
- Due to the small capacity of the high frequency vehicles used, which means less time for boarding/alighting (in contrast to the large-vehicle scenario), scenario 4 offers the lowest estimated average dwell time along the whole PT line;
- The high frequency public-transit service provided in scenario 4 is the one that provides the least number of unserved passengers along the route of the modelled PT line;
- A small decrease in the frequency of the vehicles (less vehicles) when a high frequency, metro-like service is provided leads to an improved utilisation of vehicle capacity (operator’s perspective) at the cost of an acceptable increase in the average passenger waiting time at bus stops (user’s perspective) and insignificant increase of the number of unserved passengers.

The simulation results attained showed that variant 4 (with high-frequency, small-size vehicles) would not only provide PT users with decreased average waiting times due to the small bus headways, but also with reduced total travel times along the route due to the operation of small-capacity vehicles spending less dwell times at bus stops. Moreover, in contrast to the 3 other scenarios, the high frequency small-vehicle service (scenario 4) results in the lowest number of 46 unserved passengers (those who have not alighted the bus and are still traveling in the vehicles at the end of the simulation), followed by scenario 3 with 51 passengers, and scenarios 2 and 1 with 63 and 112 passengers, respectively. In other words, compared to the scenario 1, in scenario 4 the number of the unserved passengers is more than 2 times less.

The simulation output results for scenario 4, showed that the PT operator satisfies PT demand entirely with a large number of small-size vehicles. The minimum and the maximum bus load along the sections are 24 and 36 passengers, which expressed as a percentage is 60% and 90% capacity utilisation, respectively. The average bus load is 29.3 passengers, which represents a capacity utilisation of 73.3%, indicating that around ¾ of the available passenger capacity is used.

The implementation of scenario 4.1 with reduced number of operating vehicles (from 30 in scenario 4 to 24, i.e., by 20% decrease) and increased bus headway from 120 sec. to 150 sec. (25% increase) led to an increase in the average passenger capacity utilisation of the vehicles from 73.3% (29.3 passengers on average on the bus) to 92% (36.8 passengers on the bus), which is around a 20% increase at the cost of increased average passenger waiting time at the bus stops along the route from 76 seconds to 114 seconds (50% increase). The number of the unserved passengers has slightly decreased from 46 to 40 (13% decrease), which is insignificant and can be ignored. The average total travel time remains almost unchanged – it has been slightly increased from 968 to 985 seconds.

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<th>Creating of a simulation framework and developing a simulation model implementing the novel concept of autonomous vehicles in PT and providing the flexibility to simulate the passenger transportation process along the route of a PT line, being a part of the whole PTN, as a high-frequency, metro-like PT serviced by driverless vehicles running on isolated (exclusive) lanes.</th>
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<td>Application of the developed simulation model along a route serving a PT line through different simulation scenarios, performing post-simulation analysis of the simulation output results, drawing reasonable conclusions.</td>
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Based on the literature review considering the theory and practical application of the agent-based modelling paradigm making it nowadays possible, by taking an advantage of the existing software simulation platforms, to create and represent the examined systems as multi-agent systems composed of interacting agents, the following general conclusions can be drawn:

- The urgent need for a simulation framework enabling modelling of complex and dynamic systems consisting of huge numbers of constituents that are in interaction, stimulated scientists and researchers to use the alternative of the conventional simulation modelling approaches. Agent-based modelling appears to be the appropriate and powerful enough approach providing the possibility to model complex systems, representing them as composed of large numbers of autonomous agents interacting with each other within systems’ environments through playing various roles and possessing the ability to learn and adapt.

- However, the practical application of the agent-based modelling paradigm to create agent-based models is accompanied with some inconveniences: (i) agent-based models require significant volumes of data; (ii) the requirements of computational power and speed in terms of computer processors (CPU) and computer memory (RAM) are higher; (iii) there may be some difficulties in the validation of agent-based models in those cases when they are used to model the dynamics of new or unexplored systems.

- Fortunately, the tremendous progress in information and computer technologies during the last more than two decades revealed great opportunities. In order to design, model, explore and analyse a given observed system, in addition to the conventional computer programming languages, there exists a large variety of open-source and proprietary software agent-based modelling platforms, packages and tools, providing ‘rich’ in terms of their functionality software libraries, graphical tools and visualization tools enabling post-simulation analyses, some of which can be extended in accordance with users’ goals and vision;

- The agent-based modelling approach, coupled with the extensible possibilities of the existing software agent-based modelling platforms, packages and tools, reveals new opportunities for academy and practitioners, providing them with powerful functionalities enabling to develop multi-agent models of the observed systems, simulate systems’ dynamics, examine and analyse the obtained results, and establish as a result a sound control over these complex systems that the public transport networks are.

- The results obtained through the application of the continuously developing software agent-based modelling platforms for the purposes of a large number research works in different areas, including public transport domain, describing their advantages and strengths in modelling, simulation and analysis of complex systems, are promising.

- The future efforts of PT planners and researchers in this direction should be focused on the application of the agent-based modelling approach for developing a PT multi-agent system providing the possibility to synchronise timetables of PT on a strategic level and on a tactics level to deploy operational tactics by performing fast, real-time simulations within which the main interacting actors will be passenger agents, vehicle agents, road segments and authorities, which however is an object of further studies and modelling.

The simulation output results, especially those regarding the daily person plans implemented without extra PT trips or walk legs that have replaced the planned PT legs, indicate that the system’s functioning has been satisfactorily reproduced when modelling it as a MAS. This reveals the potential of designing and implementing a monorail PTN as an alternative or supplementary (feeder) to the main bus PTN in Auckland. As demonstrated above, post-simulation analysis of the results could be performed to explore and further improve the system’s performance, which opens the door for follow-up research work including elaborating and experimenting new simulation scenarios.

### 7.2 Thesis’s contributions

A flow-chart, showing how the main findings and conclusions are linked to each other to provide the contributions of the, is given in Fig. 7.1 below.
The limitation of the existing approaches and tools for analyzing real-life complex networks, such as PTNs, place a number of new challenges for researchers and scholars in terms of the data required, methods to be applied, and software to be used. The proposed novel method, combining computer programming, statistical data, and large-scale network analyses, provides the possibility not only of examining the structure of existing real-world PT networks, but also of exploring networks' topology features and evaluating networks' efficiency – local and global – considered from networks science's point of view thus serving as a starting point in examining vulnerability and faults tolerance of complex PT networks characterized with different topologies, redesigning PT route networks and performing network reconstruction analysis. The empirical contributions of the work are threefold:

(i) The probability node-degree distributions, the regression equations empirically derived and the values of the PT topological characteristics could be used by practitioners when making decisions about re-structuring existing PT networks or designing prospective ones.

(ii) The developed software program automates and speeds up the process of extraction and processing of GTFS data of large-scale PT networks thus providing the data in a format ready for further analysis and examination of the topological properties of complex PT networks.

(iii) The method, in its last step, enables not only to introduce new PT performance measures and indicators, but also to solve two operational tasks used in practice: (a) given the desired average route length to determine the proportion of the origin-destination (O-D) PT demand that can use direct routes without transfers and the share of trips requiring transfers, and (b) given the proportion, and amount, of the O-D PT demand requiring transfers to determine the required average route length.

Once it is established what a Public-transport network topology is, what PTN’s topological properties are (as done in Chapter 3 for Auckland’s PTN and in Chapter 4 for WMN and OMN, respectively), and how efficient and fault tolerant it is (as done for WMN and OMN in Chapter 4), it is worth noting that data of actual public transport demand, bus loads (vehicles’ capacity utilization) and frequency needs to be considered in a system where passengers, vehicles and cars interact with each other, which is a subject of Chapter 4.

Chapter 4

The proposed simulation model, calibrated and validated for Auckland’s PT bus line, provides a helpful tool enabling modelers and planners to perform simulations through which the modeled system can be observed, its performance measures analyzed, and as a result, reasonable operational decisions made. The simulation output results have demonstrated that when PT demand is less than bus capacity, that capacity does not affect the average waiting time at bus stops. In cases where PT demand is high, not surprisingly, the high bus capacity, resulting in an increased number of passengers boarding the bus, indirectly causes increased passenger waiting times, unless the frequency of service is increased. These results could serve PT operators well in the trade-off situation when choosing between increased bus frequencies and larger size bus capacities, especially when the PT demand at bus stops is high. Given that the focus in the study lies on PT users, both the results obtained in the case study and the simulation model proposed here, as a basis for further research, could be of high interest to the PT sector. That is a research aimed in examining the impact of an increased frequency of service on passenger waiting times which in turn impacts the total passenger travel time on the one hand and on the other hand – in establishing to what extent the increased vehicles frequency contributes for better utilization of the unused vehicles passenger capacity. The above intent has been realised in a study which is object of Chapter 5.

In the light of the large variety of existing simulation models and tools, the proposed simulation model stands due to:

(i) the small number of input variables, which makes more realistic the chances for the model’s usage and subsequent application;

(ii) its flexibility. Through minor modifications, it would be for the model to be relatively easily and quickly adapted for modelling the passenger transportation process along a public-transport line characterised with specific parameters: route, vehicles carrying passengers, and variable passenger demand;

(iii) the ability of the model to enable evaluation of the existing system’s performance and efficiency along the route of a PT line under simulation, which would allow PT experts to effectively plan the PT service under different (existing and forecasted) conditions and scenarios.

The newly-created simulation model, implementing the novel concept of autonomous cars, provides the possibility to model passenger transportation process along a route within PT network as a high-frequency, metro-like PT service using punctual self-driving vehicles such as buses or elevated monorail tracks. The simulation output results showed that: (i) the model satisfactorily reproduces the parameters of the modelled system and (ii) through the application of the model an improved and reliable PT service was achieved.

The benefits of the application of the simulation model and the autonomous vehicle concept implements would be twofold:

(i) from PT users’ perspective – vehicles arriving at bus stops on time resulting in a reliable PT service with significantly reduced passengers waiting times at PT stops and reduced number of unserviced passengers and

(ii) from PT operators’ perspective – better vehicle capacity utilization and possibly reduced operator’s cost from drivers’ wages especially in the case of a high frequency service with driverless vehicles.

Some of the findings obtained as a result of the application of the simulation model could be taken into account in a further research work – development and application of a model on a real-life case study comprising more than one route in a public-transport network with a specific network topology.

Chapter 5

The implementation of a monorail PTN with operating autonomous trains is proposed in this thesis as a possible solution for establishing a reliable and punctual PT service which would be faster than the service provided by buses because of its independence from traffic congestion (monorail tracks, following the routes they service, will be travelling along an isolated network of straddle-type monorail tracks elevated on monorail beams). The attained results of the performed multi-agent simulation of the passenger transportation process within the proposed MAS, functioning as an interacting “passengers” and “passenger carrying” element, reveal the potential of implementing a monorail PTN. This would open the door for researchers and scientists to new ideas and opportunities in modelling, simulating, exploring and analysing complex transport systems by combining network science and public transport modelling methods, approaches and tools. Although the applied, on a case study, network science – public transit operations approach, combining a generated network with a specific (small-world) topology used as a foundation layer of a newly-designed monorail PTN on the one hand and the performed multi-agent simulations of the passenger transportation process on the other hand, does not make a claim to be detailed and exhaustive, it could be extended in the length of the present research work or for conducting new research in this direction not only taking place in Auckland, but also in other cities across the world.

In case actual passenger demand data is used, the proposed MAS could be extended and used in performing multi-agent simulations of the passenger transportation process with different size self-driving trains and frequency of service, aimed to provide PT users with a reliable service and offer transit supply capable of covering the variable travel demand. The latter could be the subject of another project, though.

Figure 7.1. Flow-chart of the main findings and conclusions
7.3 Directions for future research work

Future research work that could be a continuation of the research work presented in this thesis sub-divided in the following directions:

(1) The performed network analyses in chapters 2 and 3 consider the examined public-transport networks only on structural and route levels but on operational level. Therefore, a future research work could include components of the PT service, such as PT demand in function of employed persons (who are part of the whole population within the examined transport area/zone), the required vehicle capacity and frequency of service that should be designed and operate in a manner that meets the demand levels. Although not considering bus frequency and vehicle-kilometres travelled (and therefore operator’s cost), the presented numerical example in Chapter 2 using sample O-D demand levels between bus stop within a simplified 3-route PT network and illustrating the application of PT performance measures and indicators (such as transferring coefficient and share of O-D demand requiring transfers), could possibly be considered as a step in the this direction. The above intent could be accomplished on a real-life case study using demographic statistical data, PT O-D demand, bus loads data obtained from direct observations along the routes of more than one bus line as well as frequency of service (headways) taken from timetables and vehicle capacity.

(2) Running multi-agent monorail transit simulations with actual PT demand data comprising the entire population with the purpose to examine the dynamics of the modelled system under scenarios considering trains with different sizes and frequency of service and aimed to identify a transit supply that satisfies the existing and prospective travel demand.

(3) An application of timetable synchronisation of the trains within the monorail public transport route network as a controlling measure in achieving a reliable and punctual PT service enabling avoiding increased waiting times and missed transfers at connections stations usually resulting in walk legs instead of PT trips.

(4) Performing simulation experiments on a comparative study on monorail systems with different network topology – regular network, circular network, random network, scale-free (hub-and-spoke) network or others network types that could be of interest.

(5) Integrating the designed monorail public transport system into a coordinated multi-modal public transport network including different PT modes (buses, trains and monorail trains) which interact with each other at connection points as well as performing large-scale multi-agent simulation of the public transit operations across the whole PTN accompanied by post-simulation analysis enabling outlining of possible measures for network improvements.
(6) Originally, both the Multi-agent systems presented in chapters 4 and 6 were developed separately and they did not substitute each other. The interaction between the agents in the MAS considered in Chapter 4 is implemented along a single route of existing PT bus line, whereas the MAS modelled in Chapter 6 and simulated with MATSim comprises a newly designed public-transport network with three suggested routes. It could be possible these MAS to be used in a complimentary manner within one integrated multi-modal public-transport system including transport modes, such as buses, trains, monorail trains and ferries. For example, a possible connection point between the two multi-agent systems, respectively between the bus and the monorail transport would be a common stop or stops located in a very short walking distance from each other. A good example would be a bus and a monorail station at the Britomart Transport Centre in the Auckland’s CBD area. The possible gains resulting from a complimentary application of the above multi-agent systems would be the possibility to model, observe and analyse the interaction of these modes of transport through the passengers switching between them when making trips with transfers.
### Table A.1: Adjacency matrix

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Table A.4: Matrix of the connections between the nodes through direct route links

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### Table A.5: Matrix of the PT O-D Demand

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### Table A.6: Matrix of the PT O-D Demand not covered by direct routes (unsatisfied demand)

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Table A.7: PT measures and indicators for the developed variants of the PT route network configurations

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Figure A.1: Analytical relationship derived between $AR_{OD}$ and $AS_R$

$AR_{OD} = 3.73.AS_R^{-1}$

Figure A.2: Analytical relationship derived between $AR_{OD_d}$ and $AR_{OD}$

$AR_{OD_d} = 1.301.AR_{OD}$

Figure A.3: Analytical relationship derived between $S_{dtr}$ and $AR_{OD_d}$

$S_{dtr} = -2.328.AR_{OD_d}^2 + 5.653.AR_{OD_d} - 2.673$
SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between x (collected passenger load) and y (simulated passenger load) for direction Waikowhai – Britomart (W→B):

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SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between x (collected passenger load) and y (simulated passenger load) for direction Britomart – Waikowhai (B→W):

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<td>X Variable 1</td>
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Public-Transport Route Line Simulation Model

DECLARATIONS SEGMENT

SimTime EQU (1#60#60)+720 ;Duration of the simulation, sec.
StationsCntL1 EQU 6 ;Number of stations along route line
BusHeadway EQU 2 ;Bus headway, sec.
NumberOfDoorsBoard EQU 2 ;Number of doors to board the vehicle
NumberOfDoorsAlight EQU 2 ;Number of doors to alight the vehicle

IATatBusStop1 EQU 7.2
IATatBusStop2 EQU 9.0
IATatBusStop3 EQU 12.0
IATatBusStop4 EQU 18.0
IATatBusStop5 EQU 36.0
IATatBusStop6 EQU 1.0

PaxArrivalsAtStop1 EQU 500
PaxArrivalsAtStop2 EQU 400
PaxArrivalsAtStop3 EQU 300
PaxArrivalsAtStop4 EQU 200
PaxArrivalsAtStop5 EQU 100
PaxArrivalsAtStop6 EQU 0
PaxToAlightAtStop1 EQU 0
PaxToAlightAtStop2 EQU 4
PaxToAlightAtStop3 EQU 7
PaxToAlightAtStop4 EQU 10
PaxToAlightAtStop5 EQU 14
PaxToAlightAtStop6 EQU 17

t_BoardVeh EQU 2 ;boarding time for 1 passenger to get on a vehicle
t_AlightVeh EQU 1 ;alighting time for 1 passenger to get off a vehicle

**STORAGES**

Vehicle passenger capacity
CapacityVeh1L1 EQU 101
CapacityVeh1L1 STORAGE 40
CapacityVeh2L1 EQU 102
CapacityVeh2L1 STORAGE 40
CapacityVeh3L1 EQU 103
CapacityVeh3L1 STORAGE 40
CapacityVeh4L1 EQU 104
CapacityVeh4L1 STORAGE 40
CapacityVeh5L1 EQU 105
CapacityVeh5L1 STORAGE 40
CapacityVeh6L1 EQU 106
CapacityVeh6L1 STORAGE 40
CapacityVeh7L1 EQU 107
CapacityVeh7L1 STORAGE 40
CapacityVeh8L1 EQU 108
CapacityVeh8L1 STORAGE 40
CapacityVeh9L1 EQU 109
CapacityVeh9L1 STORAGE 40
| CapacityVeh10L1 | EQU | 110 |
| CapacityVeh10L1 | STORAGE | 40 |
| CapacityVeh11L1 | EQU | 111 |
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| CapacityVeh12L1 | EQU | 112 |
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| CapacityVeh13L1 | EQU | 113 |
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| CapacityVeh14L1 | EQU | 114 |
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| CapacityVeh16L1 | EQU | 116 |
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| CapacityVeh17L1 | EQU | 117 |
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CapacityVeh24L1 EQU 124
CapacityVeh24L1 STORAGE 40
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CapacityVeh26L1 STORAGE 40
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CapacityVeh35L1 EQU 135
CapacityVeh35L1 STORAGE 40
CapacityVeh36L1 EQU 136
CapacityVeh36L1 STORAGE 40
CapacityVeh37L1 EQU 137
CapacityVeh37L1 STORAGE 40
*-----------------------------------------------------------
Stations numbers and bus capacity

Station1L1Up  EQU  1
Station1L1Up  STORAGE  2
Station2L1Up  EQU  2
Station2L1Up  STORAGE  2
Station3L1Up  EQU  3
Station3L1Up  STORAGE  2
Station4L1Up  EQU  4
Station4L1Up  STORAGE  2
Station5L1Up  EQU  5
Station5L1Up  STORAGE  2
Station6L1Up  EQU  6
Station6L1Up  STORAGE  2

VehicleCapacity  VARIABLE  40 ; Vehicles passenger capacity
PassInVeh  VARIABLE  S*1
PassInQueue  VARIABLE  FN$QueueContent
PaxToBoard  VARIABLE  (CheckAndCalcBoardingPax(V$PassInVeh,V$PassInQueue,V$VehicleCapacity))

Initialise variable which value is used to assign a unique # for each bus running along line route
INITIAL  X$VehNumL1Up,100

Counters for the total number boarding/alighting passengers
INITIAL  X$TotalPassengersBoarded,0
INITIAL  X$TotalPassengersAlighted,0

Counter for the passengers alighting at each stop
INITIAL  X$PaxToAlight,0

Matrices initialisation with dimension M x N, where:

TravelTimesL1  MATRIX  ,1,5 ;1 bus line & 5 sections along the route of line 1 (1-2-3-4-5-6)
PaxAlightingL1up  MATRIX  ,6,2 ;6 stop numbers(1,2,3,4,5,6) & 2 columns(col.1-boarding pax,col.2-alighting pax)
PaxToAlightAtStop  MATRIX  ,1,6
MATRICES ELEMENTS

**Initialisation of the TravelTimesL1 matrix elements (Travel times along the sections of the route)**

INITIAL MX$TravelTimesL1(1,1),180
INITIAL MX$TravelTimesL1(1,2),180
INITIAL MX$TravelTimesL1(1,3),180
INITIAL MX$TravelTimesL1(1,4),180
INITIAL MX$TravelTimesL1(1,5),180

**------ Passengers alighting the bus at each stop**

INITIAL MX$PaxAlightingL1up(1,2),PaxToAlightAtStop1
INITIAL MX$PaxAlightingL1up(2,2),PaxToAlightAtStop2
INITIAL MX$PaxAlightingL1up(3,2),PaxToAlightAtStop3
INITIAL MX$PaxAlightingL1up(4,2),PaxToAlightAtStop4
INITIAL MX$PaxAlightingL1up(5,2),PaxToAlightAtStop5
INITIAL MX$PaxAlightingL1up(6,2),PaxToAlightAtStop6

**------ Accumulate the number of passengers who alighted at each bus stop**

INITIAL MX$PaxToAlightAtStop(1,1),0
INITIAL MX$PaxToAlightAtStop(1,2),0
INITIAL MX$PaxToAlightAtStop(1,3),0
INITIAL MX$PaxToAlightAtStop(1,4),0
INITIAL MX$PaxToAlightAtStop(1,5),0
INITIAL MX$PaxToAlightAtStop(1,6),0

FUNCTION

```
FUNCTION P3,M6
1,Q1/2,Q2/3,Q3/4,Q4/5,Q5/6,Q6
```

**SysTime**

```
TABLE MP20,900,5,24
```
MODELING SEGMENTS

MODELING SEGMENT I

Passenger arrivals at bus stops 1, 2, ..., 6 in direction 1-6

GENERATE IATatBusStop1,,0,PaxArrivalsAtStop1 ; Passenger interarrival times at bus stop 1
QUEUE 1
TERMINATE

GENERATE IATatBusStop2,,180,PaxArrivalsAtStop2
QUEUE 2
TERMINATE

GENERATE IATatBusStop3,,360,PaxArrivalsAtStop3
QUEUE 3
TERMINATE

GENERATE IATatBusStop4,,540,PaxArrivalsAtStop4
QUEUE 4
TERMINATE

GENERATE IATatBusStop5,,720,PaxArrivalsAtStop5
QUEUE 5
TERMINATE

GENERATE IATatBusStop6,,0,PaxArrivalsAtStop6
QUEUE 6
TERMINATE

Modeling bus movements along route line 1 in direction 1-6

GENERATE (BusHeadway#60),,0 ; vehicles interarrival time
MARK 20
SAVEVALUE VehNumL1Up+,1
ASSIGN 1,X$VehNumL1Up
ASSIGN StationsPassThrough,StationsCntL1
ASSIGN 2,0

162
NextStopL1
ASSIGN 2+,1
ASSIGN 3,P2

VehEntersStation
ENTER P3
TEST L P3,StationsCntL1,GetOffAtLastStation

PaxEnterVehicle
ENTER P1,P$PaxToBoardTheVeh
DEPART P3,P$PaxToBoardTheVeh
LEAVE P3 TRANSFER,Go2NextStation

PaxLeaveVehicle
SAVEVALUE PaxToAlight,(CheckAndCalcAlightingPax(V$PassInVeh,MX$PaxAlightingL1up(P3,2)))
SAVEVALUE TotalPassengersAlighted+, (CheckAndCalcAlightingPax(V$PassInVeh,MX$PaxAlightingL1up(P3,2)))
MSAVEVALUE PaxToAlightAtStop+,1,P3,X$PaxToAlight
LEAVE P1,(CheckAndCalcAlightingPax(V$PassInVeh,MX$PaxAlightingL1up(P3,2)))
ADVANCE ((X$PaxToAlight#t_AlightVeh)/NumberOfDoorsAlight)
ASSIGN PaxToBoardTheVeh,V$PaxToBoard
SAVEVALUE TotalPassengersBoarded+,V$PaxToBoard
ADVANCE ((V$PaxToBoard#t_BoardVeh)/NumberOfDoorsBoard)
ENTER P1,P$PaxToBoardTheVeh
DEPART P3,P$PaxToBoardTheVeh
LEAVE P3

Go2NextStation
ADVANCE MX$TravelTimesL1(1,P3)
TEST G P$StationsPassThrough,0,LeavesSystem
ASSIGN StationsPassThrough-,1
TRANSFER,NextStopL1

GetOffAtLastStation
SAVEVALUE PaxToAlight,(CheckAndCalcAlightingPax(V$PassInVeh,V$PassInVeh))
SAVEVALUE TotalPassengersAlighted+, (CheckAndCalcAlightingPax(V$PassInVeh,V$PassInVeh))
MSAVEVALUE PaxToAlightAtStop+,1,P3,X$PaxToAlight
LEAVE P1,(CheckAndCalcAlightingPax(V$PassInVeh,V$PassInVeh))
ADVANCE ((V$PassInVeh#t_AlightVeh)/NumberOfDoorsAlight)

LeaveStation
LEAVE P3
TABULATE SysTime

LeavesSystem
TERMINATE

************************************************************************************
* MODELING SEGMENT II
* SIMULATION CLOCK
*
**************************************
----------- Simulation clock modeling the duration of the simulation
GENERATE SimTime
TERMINATE 1
**************************************

START 1 ;Start simulation
**************************************

* PROCEDURES *
**************************************
PROCEDURE CheckAndCalcBoardingPax(Param1,Param2,Param3)
BEGIN
TEMPORARY tmpPassInVehicle,tmpQueueContent,tmpVehicleCapacity,tmpPassToBoard,tmpAvailableSpace;
tmpPassInVehicle = Param1;
tmpQueueContent = Param2;
tmpVehicleCapacity = Param3;
tmpAvailableSpace = (tmpVehicleCapacity - tmpPassInVehicle);
IF (tmpQueueContent <= tmpAvailableSpace) THEN
BEGIN
  tmpPassToBoard = tmpQueueContent;
  RETURN tmpPassToBoard;
END;
ELSE
BEGIN
  tmpPassToBoard = tmpAvailableSpace;
  RETURN tmpPassToBoard;
END;
END;

PROCEDURE CheckAndCalcAlightingPax(Par1,Par2)
BEGIN
TEMPORARY tmpPaxInVehicle,tmpPaxAlighting;
tmpPaxInVehicle = Par1;
tmpPaxAlighting = Par2;
IF (tmpPaxAlighting > tmpPaxInVehicle) THEN
BEGIN
  RETURN tmpPaxInVehicle;
END;
ELSE
BEGIN
  RETURN tmpPaxAlighting;
END;
END;
APPENDIX D – SUMMARY OUTPUT FOR THE PERFORMED LINEAR REGRESSION ANALYSYS IN CHAPTER 5

SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between the observed versus simulated passengers alighted the bus in scenario 1:

<table>
<thead>
<tr>
<th>Table D.1: Regression statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression Statistics</td>
</tr>
<tr>
<td>Multiple R 0.990120938</td>
</tr>
<tr>
<td>R Square 0.980339472</td>
</tr>
<tr>
<td>Adjusted R Square 0.973785962</td>
</tr>
<tr>
<td>Standard Error 20.60663324</td>
</tr>
<tr>
<td>Observations 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.2: ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Regression</td>
</tr>
<tr>
<td>Residual</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.3: Regression coefficients, standard errors and t statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
</tr>
<tr>
<td>Intercept</td>
</tr>
<tr>
<td>X Variable 1</td>
</tr>
</tbody>
</table>

SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between the observed versus simulated passengers alighted the bus in scenario 2:

<table>
<thead>
<tr>
<th>Table D.4: Regression statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression Statistics</td>
</tr>
<tr>
<td>Multiple R 0.996768452</td>
</tr>
<tr>
<td>R Square 0.993547347</td>
</tr>
<tr>
<td>Adjusted R Square 0.991396463</td>
</tr>
<tr>
<td>Standard Error 13.2715234</td>
</tr>
<tr>
<td>Observations 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.5: ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Regression</td>
</tr>
<tr>
<td>Residual</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.6: Regression coefficients, standard errors and t statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
</tr>
<tr>
<td>Intercept</td>
</tr>
<tr>
<td>X Variable 1</td>
</tr>
</tbody>
</table>

SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between the observed versus simulated passengers alighted the bus in scenario 3:

<table>
<thead>
<tr>
<th>Table D.7: Regression statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression Statistics</td>
</tr>
<tr>
<td>Multiple R 0.998879067</td>
</tr>
<tr>
<td>R Square 0.99775939</td>
</tr>
<tr>
<td>Adjusted R Square 0.99701252</td>
</tr>
<tr>
<td>Standard Error 7.907802055</td>
</tr>
<tr>
<td>Observations 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.8: ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Regression</td>
</tr>
<tr>
<td>Residual</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.9: Regression coefficients, standard errors and t statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
</tr>
<tr>
<td>Intercept</td>
</tr>
<tr>
<td>X Variable 1</td>
</tr>
</tbody>
</table>
SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between the observed versus simulated passengers alighted the bus in scenario 4:

<table>
<thead>
<tr>
<th>Table D.10: Regression statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression Statistics</td>
<td></td>
</tr>
<tr>
<td>Multiple R</td>
<td>0.980001058</td>
</tr>
<tr>
<td>R Square</td>
<td>0.960402073</td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.947202764</td>
</tr>
<tr>
<td>Standard Error</td>
<td>29.26708475</td>
</tr>
<tr>
<td>Observations</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.11: ANOVA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>SS</td>
</tr>
<tr>
<td>Regression</td>
<td>1</td>
</tr>
<tr>
<td>Residual</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.12: Regression coefficients, standard errors and t statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Intercept</td>
<td>53.6</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.79</td>
</tr>
</tbody>
</table>

SUMMARY OUTPUT of the results obtained from the linear regression analysis performed in identifying the linear relationship between the observed versus simulated passengers alighted the bus in scenario 4.1:

<table>
<thead>
<tr>
<th>Table D.13: Regression statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression Statistics</td>
<td></td>
</tr>
<tr>
<td>Multiple R</td>
<td>0.986972734</td>
</tr>
<tr>
<td>R Square</td>
<td>0.974115178</td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.965486904</td>
</tr>
<tr>
<td>Standard Error</td>
<td>23.15455319</td>
</tr>
<tr>
<td>Observations</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.14: ANOVA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
<td>SS</td>
</tr>
<tr>
<td>Regression</td>
<td>1</td>
</tr>
<tr>
<td>Residual</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table D.15: Regression coefficients, standard errors and t statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficients</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Intercept</td>
<td>58.4</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.778</td>
</tr>
</tbody>
</table>
E.1. Contents of the configuration file “Config.xml”

```xml
<module name="global">
  <param name="randomSeed" value="4711" />
</module>

<module name="network">
  <param name="inputNetworkFile" value="PtNetwork.xml" />
</module>

<module name="plans">
  <param name="inputPlansFile" value="Population.xml" />
</module>

<module name="transit">
  <param name="useTransit" value="true" />
  <param name="transitScheduleFile" value="TransitSchedule.xml" />
  <param name="vehiclesFile" value="TransitVehicles.xml" />
  <param name="transitModes" value="pt" />
</module>

<module name="changeMode">
  <param name="ignoreCarAvailability" value="true" />
  <param name="modes" value="pt" />
</module>

<module name="TimeAllocationMutator">
  <param name="mutationRange" value="7200.0" />
</module>

<module name="controller">
  <param name="firstIteration" value="0" />
  <param name="lastIteration" value="0" />
  <param name="eventsFileFormat" value="xml" />
  <param name="writeEventsInterval" value="1" />
  <param name="writePlansInterval" value="50" />
  <param name="mobsim" value="qsim" />
</module>

<module name="qsim">
  <param name="startTime" value="05:00:00" />
  <param name="endTime" value="19:00:00" />
  <param name="simStarttimeInterpretation" value="onlyUseStarttime" />
  <param name="removeStuckVehicles" value="false" />
  <param name="snapshotStyle" value="queue" />
</module>

<module name="planCalcScore">
  <param name="BrainExpBeta" value="1.0" />
  <param name="lateArrival" value="-18" />
  <param name="earlyDeparture" value="-18" />
  <param name="performing" value="+6" />
  <param name="traveling" value="-6" />
  <param name="constantWalk" value="0" />
  <param name="marginalUtlOfDistanceWalk" value="0" />
  <param name="travelingWalk" value="-12" />
  <param name="activityType_0" value="h" />
  <param name="activityPriority_0" value="1" />
  <param name="activityTypicalDuration_0" value="12:00:00" />
  <param name="activityType_1" value="w" />
  <param name="activityPriority_1" value="1" />
  <param name="activityTypicalDuration_1" value="08:00:00" />
</module>

<module name="strategy">
  <param name="ModuleProbability_1" value="0.8" />
  <param name="Module_1" value="ChangeExpBeta" />
</module>

<module name="transitRouter">
  <param name="additionalTransferTime" value="60.0" />
  <param name="extensionRadius" value="1000.0" />
  <param name="maxBeelineWalkConnectionDistance" value="500.0" />
  <param name="searchRadius" value="10000.0" />
</module>
```

<config>
```
E.2. Contents of the monorail train public-transport route network file “PtNetwork.xml”

<!DOCTYPE network SYSTEM "http://www.matsim.org/files/dtd/network_v2.dtd">

<network>
  <nodes>
  </nodes>
</network>
```xml
  <vehicle id="109" type="1"/>
  <vehicle id="107" type="1"/>
  <vehicle id="103" type="1"/>
  <vehicle id="102" type="1"/>
  <vehicle id="101" type="1"/>
  <vehicle id="100" type="1"/>
</vehicleDefinitions>
```

### E.3. Content of the monorail trains data file “TransitVehicles.xml”

```
<vehicleType id="1">
  <description><![CDATA[]]></description>
  <capacity>
    <seats persons="15"/>
    <standingRoom persons="30"/>
    <length meter="10.00"/>
  </capacity>
</vehicleType>
```

**Line 1 - right directions**

- in the morning
  - vehicle id="101" type="1"
  - vehicle id="100" type="1"
- in the afternoon
  - vehicle id="109" type="1"
```
<vehicle id="111" type="1"/>
<vehicle id="113" type="1"/>
<vehicle id="115" type="1"/>

<vehicle id="110" type="1"/>
<vehicle id="108" type="1"/>
<vehicle id="106" type="1"/>
<vehicle id="104" type="1"/>
<vehicle id="102" type="1"/>

<vehicle id="114" type="1"/>
<vehicle id="116" type="1"/>
<vehicle id="112" type="1"/>
<vehicle id="201" type="1"/>
<vehicle id="203" type="1"/>
<vehicle id="205" type="1"/>
<vehicle id="207" type="1"/>
<vehicle id="209" type="1"/>
<vehicle id="211" type="1"/>
<vehicle id="213" type="1"/>
<vehicle id="215" type="1"/>
<vehicle id="202" type="1"/>
<vehicle id="204" type="1"/>
<vehicle id="206" type="1"/>
<vehicle id="208" type="1"/>
<vehicle id="210" type="1"/>
<vehicle id="212" type="1"/>
<vehicle id="214" type="1"/>
<vehicle id="216" type="1"/>

<vehicle id="301" type="1"/>
<vehicle id="303" type="1"/>
<vehicle id="305" type="1"/>
<vehicle id="307" type="1"/>
<vehicle id="309" type="1"/>
<vehicle id="311" type="1"/>
<vehicle id="313" type="1"/>
<vehicle id="315" type="1"/>
<vehicle id="302" type="1"/>
<vehicle id="304" type="1"/>
<vehicle id="306" type="1"/>
<vehicle id="308" type="1"/>
<vehicle id="310" type="1"/>
<vehicle id="312" type="1"/>
<vehicle id="314" type="1"/>
<vehicle id="316" type="1"/>

<vehicleDefinitions>

E.4. Content of the monorail trains timetable file “TransitSchedule.xml”

<transitSchedule>
<transitStops>

<stopFacility id="s1r1" x="1.9454194986135144E7" y="-4419296.0" linkRefId="-44128_0"/>
<stopFacility id="s1r2" x="1.9454573886873007E7" y="-4418532.0" linkRefId="-44128_3"/>
<stopFacility id="s1r3" x="1.9455669160889093E7" y="-4418540.0" linkRefId="-44128_7"/>
<stopFacility id="s1r4" x="1.94562546074886E7" y="-4419022.0" linkRefId="-44128_8"/>

<stopFacility id="s1o1" x="1.94562546074886E7" y="-4419022.0" linkRefId="-73387_0"/>
<stopFacility id="s1o2" x="1.9455669160889093E7" y="-4418541.0" linkRefId="-73387_1"/>
<stopFacility id="s1o3" x="1.9455669160889093E7" y="-4418540.0" linkRefId="-73387_7"/>
<stopFacility id="s1o4" x="1.9454194986135144E7" y="-4419297.0" linkRefId="-73387_8"/>

<stopFacility id="s2r1" x="1.9454573886873007E7" y="-4418533.0" linkRefId="-40824_0"/>
<stopFacility id="s2r2" x="1.9454194986135144E7" y="-4419297.0" linkRefId="-73387_3"/>
<stopFacility id="s2r3" x="1.9453439273683676E7" y="-4417535.0" linkRefId="-40824_13"/>

<transStops/>
</transitSchedule>
<transitLine id="Line2">
  <!-- right direction -->
  <transitRoute id="s2r1TOs2r3">
    <transportMode>pt</transportMode>
    <routeProfile>
      <stop refId="s2r1" departureOffset="00:00:00" />
      <stop refId="s2r2" arrivalOffset="00:01:50" departureOffset="00:02:20" awaitDeparture="true" />
      <stop refId="s2r3" arrivalOffset="00:04:35" departureOffset="00:05:05" awaitDeparture="true" />
    </routeProfile>
    <route>
      <link refId="-40824_0" />
      <link refId="-40824_1" />
      <link refId="-40824_2" />
      <link refId="-40824_3" />
      <link refId="-40824_4" />
      <link refId="-40824_5" />
      <link refId="-40824_6" />
      <link refId="-40824_7" />
      <link refId="-40824_8" />
      <link refId="-40824_9" />
      <link refId="-40824_10" />
      <link refId="-40824_11" />
      <link refId="-40824_12" />
      <link refId="-40824_13" />
    </route>
    <departures>
      <!-- in the morning -->
      <departure id="01" departureTime="07:20:00" vehicleRefId="201" />
      <departure id="02" departureTime="07:35:00" vehicleRefId="203" />
      <departure id="03" departureTime="08:00:00" vehicleRefId="205" />
      <departure id="04" departureTime="08:15:00" vehicleRefId="207" />
      <!-- in the afternoon -->
      <departure id="05" departureTime="17:00:00" vehicleRefId="209" />
      <departure id="06" departureTime="17:15:00" vehicleRefId="211" />
      <departure id="07" departureTime="17:30:00" vehicleRefId="213" />
      <departure id="08" departureTime="17:45:00" vehicleRefId="215" />
    </departures>
  </transitRoute>
  <!-- opposite direction -->
  <transitRoute id="s2o1TOs2o3">
    <transportMode>pt</transportMode>
    <routeProfile>
      <stop refId="s2o1" departureOffset="00:00:00" />
      <stop refId="s2o2" arrivalOffset="00:01:50" departureOffset="00:02:20" awaitDeparture="true" />
      <stop refId="s2o3" arrivalOffset="00:04:35" departureOffset="00:05:05" awaitDeparture="true" />
    </routeProfile>
    <route>
      <link refId="-46434_0" />
      <link refId="-46434_1" />
      <link refId="-46434_2" />
      <link refId="-46434_3" />
      <link refId="-46434_4" />
      <link refId="-46434_5" />
      <link refId="-46434_6" />
      <link refId="-46434_7" />
      <link refId="-46434_8" />
      <link refId="-46434_9" />
      <link refId="-46434_10" />
      <link refId="-46434_11" />
      <link refId="-46434_12" />
      <link refId="-46434_13" />
    </route>
    <departures>
      <!-- in the morning -->
      <departure id="01" departureTime="07:15:00" vehicleRefId="202" />
      <departure id="02" departureTime="07:30:00" vehicleRefId="204" />
      <departure id="03" departureTime="07:45:00" vehicleRefId="206" />
      <departure id="04" departureTime="08:00:00" vehicleRefId="208" />
      <!-- in the afternoon -->
      <departure id="05" departureTime="17:00:00" vehicleRefId="210" />
      <departure id="06" departureTime="17:15:00" vehicleRefId="212" />
      <departure id="07" departureTime="17:30:00" vehicleRefId="214" />
      <departure id="08" departureTime="17:45:00" vehicleRefId="216" />
    </departures>
  </transitRoute>
</transitLine>

<transitLine id="Line3">
  <!-- right direction -->
  <transitRoute id="s3r1TOs3r5">
    <transportMode>pt</transportMode>
    <routeProfile>
      <stop refId="s3r1" departureOffset="00:00:00" />
      <stop refId="s3r2" arrivalOffset="00:01:30" departureOffset="00:02:00" awaitDeparture="true" />
    </routeProfile>
    <route>
      <link refId="-46434_0" />
      <link refId="-46434_1" />
      <link refId="-46434_2" />
      <link refId="-46434_3" />
      <link refId="-46434_4" />
      <link refId="-46434_5" />
      <link refId="-46434_6" />
      <link refId="-46434_7" />
      <link refId="-46434_8" />
      <link refId="-46434_9" />
      <link refId="-46434_10" />
      <link refId="-46434_11" />
      <link refId="-46434_12" />
      <link refId="-46434_13" />
    </route>
    <departures>
      <!-- in the morning -->
      <departure id="01" departureTime="07:15:00" vehicleRefId="202" />
      <departure id="02" departureTime="07:30:00" vehicleRefId="204" />
      <departure id="03" departureTime="07:45:00" vehicleRefId="206" />
      <departure id="04" departureTime="08:00:00" vehicleRefId="208" />
      <!-- in the afternoon -->
      <departure id="05" departureTime="17:00:00" vehicleRefId="210" />
      <departure id="06" departureTime="17:15:00" vehicleRefId="212" />
      <departure id="07" departureTime="17:30:00" vehicleRefId="214" />
      <departure id="08" departureTime="17:45:00" vehicleRefId="216" />
    </departures>
  </transitRoute>
</transitLine>
E.5. Content of the synthetic population file “Population.xml”
From 3 to 1, i.e. from s2r1 to s2r3

<person id="73" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>

From 3 to 1, i.e. from s2r1 to s2r3

<person id="74" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>

From 3 to 1, i.e. from s2r1 to s2r3

<person id="75" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>

From 3 to 1, i.e. from s2r1 to s2r3

<person id="76" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>

From 3 to 1, i.e. from s2r1 to s2r3

<person id="77" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>

From 3 to 1, i.e. from s2r1 to s2r3

<person id="78" employed="yes">
  <plan selected="no">
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-40824_13" x="1.9453439273689367E7" y="-4417538.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-40824_0" x="1.945457522944761E7" y="-4418533.0" />
  </plan>
</person>
From 2 To 8, i.e. from s1r1 to s1r4

<table>
<thead>
<tr>
<th>Person ID</th>
<th>Employment</th>
<th>Plan Selected</th>
<th>Activity Details</th>
</tr>
</thead>
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<tr>
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<td>No</td>
<td>07:14:30-17:00:00</td>
</tr>
<tr>
<td>115</td>
<td>Yes</td>
<td>No</td>
<td>07:14:30-17:00:00</td>
</tr>
<tr>
<td>116</td>
<td>Yes</td>
<td>No</td>
<td>07:14:30-17:00:00</td>
</tr>
<tr>
<td>117</td>
<td>Yes</td>
<td>No</td>
<td>07:14:30-17:00:00</td>
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<tr>
<td>118</td>
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<td>119</td>
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<td>120</td>
<td>Yes</td>
<td>No</td>
<td>07:14:30-17:00:00</td>
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<leg mode="pt" />
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<act type="w" link="-40824_3" x="1.9454942336190876E7" y="-4417369.0" end_time="17:00:00"/>

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<leg mode="pt">
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</leg>

<act type="h" link="-44128_0" x="1.9454194986135144E7" y="-4419299.0" end_time="07:14:30"/>
From2To4, i.e. from s1r1 to s2r2

Person id="155" employed="yes"
<plan selected="no">
<act type="h" link="-44128_0" x="1.9454194986135144E7" y="-4419299.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-40824_3" x="1.9454942336190876E7" y="-4417369.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_0" x="1.9454194986135144E7" y="-4419299.0" />
</plan>

From2To4, i.e. from s1r1 to s2r2

Person id="156" employed="yes"
<plan selected="no">
<act type="h" link="-44128_0" x="1.9454194986135144E7" y="-4419299.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-40824_3" x="1.9454942336190876E7" y="-4417369.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_0" x="1.9454194986135144E7" y="-4419299.0" />
</plan>

From3To6, i.e. from s1r2 to s3o4

Person id="5" employed="yes"
<plan selected="no">
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
</plan>

From3To6, i.e. from s1r2 to s3o4

Person id="157" employed="yes"
<plan selected="no">
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
</plan>

From3To6, i.e. from s1r2 to s3o4

Person id="158" employed="yes"
<plan selected="no">
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
</plan>

From3To6, i.e. from s1r2 to s3o4

Person id="159" employed="yes"
<plan selected="no">
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0"
end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0"
end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
</plan>
<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="167" employed="yes">
  <plan selected="no">
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="168" employed="yes">
  <plan selected="no">
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="169" employed="yes">
  <plan selected="no">
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="170" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="171" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="172" employed="yes">
  <plan selected="no">
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>

<-- From3To6, i.e. from s1r2 to s3o4 -->
<person id="173" employed="yes">
  <plan selected="no">
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="-47260_23" x="1.9455358411525078E7" y="-4420428.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="-44128_3" x="1.9454573886873007E7" y="-4418535.0" />
  </plan>
</person>
From 4 to 5, i.e. from s3o1 to s3o3

From 8 to 3, i.e. from s1o1 to s1o3

From 8 to 3, i.e. from s1o1 to s1o3

From 8 to 3, i.e. from s1o1 to s1o3

From 8 to 3, i.e. from s1o1 to s1o3
197
From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 213, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 214, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 215, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 216, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 217, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 218, Employed: yes

Plan

- From 8 To 4, i.e. from s1o1 to s3r5

Person ID: 219, Employed: yes

Plan
<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
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<leg />
<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" />
</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
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</plan>
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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
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</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
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</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
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<leg />
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</plan>
</person>

<plan selected="no">
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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
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</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" />
</plan>
</person>

<plan selected="no">
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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
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</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" />
</plan>
</person>

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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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</plan>
</person>

<plan selected="no">
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<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" end_time="07:14:30" />
<leg />
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<leg />
<act type="h" link="73387_0" x="1.945625460574886E7" y="4419023.0" />
</plan>
</person>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="227" employed="yes">
<plan selected="no">
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<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="228" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="229" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="230" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="231" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="232" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg mode="pt">
</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>

<-- From8To4, i.e. from s1o1 to s3r5 -->
<person id="233" employed="yes">
<plan selected="no">
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</leg>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg mode="pt">
</leg>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" />
</plan>
</person>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0"/>

</plan>

<-- FromTTo4, i.e. from s1o1 to s3r5 -->
<person id="248" employed="yes">
<plan selected="no">
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<leg/>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0"/>
</plan>
</person>

<-- FromTTo4, i.e. from s1o1 to s3r5 -->
<person id="249" employed="yes">
<plan selected="no">
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0"/>
</plan>
</person>

<-- FromTTo4, i.e. from s1o1 to s3r5 -->
<person id="250" employed="yes">
<plan selected="no">
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<leg/>
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417367.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73387_0" x="1.945625460574886E7" y="-4419023.0"/>
</plan>
</person>

<-- From9To3, i.e. from s3r1 to s1o3 -->
<person id="9" employed="yes">
<plan selected="no">
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73387_5" x="1.9454573886873007E7" y="-4418532.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0"/>
</plan>
</person>

<-- From9To3, i.e. from s3r1 to s1o3 -->
<person id="50" employed="yes">
<plan selected="no">
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73387_5" x="1.9454573886873007E7" y="-4418532.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0"/>
</plan>
</person>

<-- From9To3, i.e. from s3r1 to s1o3 -->
<person id="51" employed="yes">
<plan selected="no">
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73387_5" x="1.9454573886873007E7" y="-4418532.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0"/>
</plan>
</person>

<-- From9To3, i.e. from s3r1 to s1o3 -->
<person id="52" employed="yes">
<plan selected="no">
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
<leg/>
<act type="w" link="73387_5" x="1.9454573886873007E7" y="-4418532.0" end_time="17:00:00" />
<leg/>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0"/>
</plan>
</person>

204
<person id="52" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="53" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="54" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="55" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="56" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="57" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="58" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="59" employed="yes">
  <plan selected="no">
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    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>

<person id="60" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73387_5" x="1.9454573888673007E7" y="-4418532.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420763.0" />
  </plan>
</person>
From 9 To 3, i.e. from s3r1 to s1o3

<person id="59" employed="yes"/>

<plan selected="no">
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0" end_time="07:14:30"/>
  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="60" employed="yes"/>

<plan selected="no">
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0" end_time="07:14:30"/>
  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="61" employed="yes"/>

<plan selected="no">
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  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="62" employed="yes"/>

<plan selected="no">
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  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="63" employed="yes"/>

<plan selected="no">
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0" end_time="07:14:30"/>
  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="64" employed="yes"/>

<plan selected="no">
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0" end_time="07:14:30"/>
  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>

<person id="65" employed="yes"/>

<plan selected="no">
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0" end_time="07:14:30"/>
  <leg mode="pt"/>
  <act type="w" link="73387_5" x="1.9454573886873007E7" y="4418532.0" end_time="17:00:00"/>
  <leg mode="pt"/>
  <act type="h" link="73553_0" x="1.945621086357706E7" y="4420763.0"/>
</plan>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>

<html>

<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <title>Document Title</title>
</head>
<body>

<p>From 9 To 4, i.e. from s3r1 to s3r5: 

- Person ID: 14, Employed: Yes
  <plan selected="no">
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    <leg mode="pt">
    </leg>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt">
    </leg>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>

- Person ID: 15, Employed: Yes
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt">
    </leg>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt">
    </leg>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>

- Person ID: 16, Employed: Yes
  <plan selected="no">
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    <leg mode="pt">
    </leg>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt">
    </leg>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>

</body>
</html>
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />

<plan>
  <person id="28" employed="yes">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="29" employed="yes">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="30" employed="yes">
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    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="31" employed="yes">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="32" employed="yes">
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    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="33" employed="yes">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<plan>
  <person id="34" employed="yes">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
    <leg mode="pt" />
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
    <leg mode="pt" />
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />
  </plan>
</person>

<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />

<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />

<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30" />
<leg mode="pt" />
<act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00" />
<leg mode="pt" />
<act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" />

From 9 To 4, i.e. from s3r1 to s3r5
From 9 To 4, i.e. from s3r1 to s3r5

<person id="35" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="36" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="37" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="38" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="39" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="40" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>

From 9 To 4, i.e. from s3r1 to s3r5

<person id="41" employed="yes">
  <plan selected="no">
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0" end_time="07:14:30"/>
    <leg mode="pt"/>
    <act type="w" link="73553_26" x="1.945494269194217E7" y="-4417369.0" end_time="17:00:00"/>
    <leg mode="pt"/>
    <act type="h" link="73553_0" x="1.945621086357706E7" y="-4420764.0"/>
  </plan>
</person>
APPENDIX F – MULTI-AGENT SIMULATION OUTPUT RESULTS

Figure F.1. Train schedule of route s1r1T0s1r4 servicing monorail Line 1 in right direction

Figure F.2. Train schedule of route s1o1T0s1o4 servicing monorail Line 1 in opposite direction
Figure F.3. Train schedule of route s2r1TOs2r3 servicing monorail Line 2 in right direction

Figure F.4. Train schedule of route s2o1TOs2o3 servicing monorail Line 2 in opposite direction
Figure F.5. Train schedule of route s3r1TOs3r5 servicing monorail Line 3 in right direction

Figure F.6. Train schedule of route s3o1TOs3o5 servicing monorail Line 3 in opposite direction
Figure F.7. Passengers entering/leaving the stations along route s1r1TOs1r4 servicing Line 1 in right direction

Figure F.8. Passengers entering/leaving the stations along route s1o1TOs1o4 servicing Line 2 in opposite direction
Figure F.9. Passengers entering/leaving the stations along route s2r1TOs2r3 servicing Line 2 in right direction.

Figure F.10. Passengers entering/leaving the stations along route s2o1TOs2o3 servicing Line 2 in opposite direction.
Figure F.11. Passengers entering/leaving the stations along route s3r1TOs3r5 servicing Line 3 in right direction

Figure F.12. Passengers entering/leaving the stations along route s3o1TOs3o5 servicing Line 3 in opposite direction
Figure F.13. Train loads along route s1r1TOs1r4 servicing monorail Line 1 in right direction

Figure F.14. Train loads along route s1o1TOs1o4 servicing monorail Line 1 in opposite direction
Figure F.15. Train loads along route s2r1TOs2r3 servicing monorail Line 2 in right direction

Figure F.16. Train loads along route s2o1TOs2o3 servicing monorail Line 2 in opposite direction
Figure F.17. Train loads along route s3r1TOs3r5 servicing monorail Line 3 in right direction

Figure F.18. Train loads along route s3o1TOs3o5 servicing monorail Line 3 in opposite direction
Figure F.19. Passenger flows between the stops along route s1r1TOs1r4 servicing monorail Line 1 in right direction

Figure F.20. Passenger flows between the stops along route s1o1TOs1o4 servicing monorail Line 1 in opposite direction
Figure F.21. Passenger flows between the stops along route s2r1TOs2r3 servicing monorail Line 2 in right direction.

Figure F.22. Passenger flows between the stops along route s2o1TOs2o3 servicing monorail Line 2 in opposite direction.
Figure F.23. Passenger flows between the stops along route s3r1TOs3r5 servicing monorail Line 3 in right direction

Figure F.24. Passenger flows between the stops along route s3o1TOs3o5 servicing monorail Line 3 in opposite direction
Table F.1. Passenger transfers between the lines 1 and 2 at monorail stop 3

<table>
<thead>
<tr>
<th>From/To</th>
<th>Line1</th>
<th>Line2</th>
<th>Start / End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line1</td>
<td>0</td>
<td>85</td>
<td>58</td>
</tr>
<tr>
<td>Line2</td>
<td>35</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Start / End</td>
<td>58</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure F.25. Passenger transfers between the lines 1 and 2 at monorail stop 3

Table F.2. Passenger transfers between the lines 1 and 3 at monorail stop 7

<table>
<thead>
<tr>
<th>From/To</th>
<th>Line1</th>
<th>Line3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line1</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>Line3</td>
<td>88</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure F.26. Passenger transfers between the lines 1 and 3 at monorail stop 7


Caliper Corporation (2013). "TransCAD 6.0 r2 64-Bit Base;"


IBM Corporation (2012). "IBM® SPSS® Statistics, version 21


Microsoft Corporation (2010). Microsoft® Office Excel 2010


236


