

# Contents

<b>Abstract</b>	<b>v</b>
<b>Publications</b>	<b>vii</b>
<b>Acknowledgements</b>	<b>xvii</b>
<b>List of Figures</b>	<b>xxv</b>
<b>List of Tables</b>	<b>xxvii</b>
<b>List of Abbreviations</b>	<b>xxix</b>
<b>List of Symbols</b>	<b>xxxi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Overview and Research Motivation . . . . .	1
1.2 Background and Significance of the Research . . . . .	2
1.3 Research Problem . . . . .	11
1.4 Scope of Research and Objectives . . . . .	12
1.5 Research Methodology . . . . .	13
1.6 Thesis Outline . . . . .	15
<b>2 Optimal Combinations of Selected Tactics for Public-Transport Transfer Synchronization</b>	<b>21</b>
2.1 Abstract . . . . .	21
2.2 Introduction . . . . .	22
2.3 Formulation and Modeling Framework . . . . .	24
2.3.1 Model Description . . . . .	24
2.3.2 Formulation and Properties of Holding Tactic . . . . .	27
2.3.3 Formulation and Properties of Skip-Stop and Skip-Segment Tactics	28
2.3.4 Formulation and Properties of Transfers . . . . .	31

2.3.5	Objective Function . . . . .	32
2.3.6	Constraints . . . . .	32
2.3.7	Model Optimization . . . . .	35
2.4	Case Study of Real-Time Tactics Implementation . . . . .	35
2.4.1	Data . . . . .	36
2.4.2	Network Simulation . . . . .	37
2.5	Result and Analysis . . . . .	37
2.5.1	Simulation of the Case Study . . . . .	38
2.5.2	Validation Using Simulation . . . . .	39
2.5.3	Results and Performance of the Proposed Model . . . . .	39
2.6	Concluding Remarks . . . . .	46
<b>3</b>	<b>A Robust, Tactic-Based, Real-Time Framework for Public-Transport Transfer Synchronization</b>	<b>49</b>
3.1	Abstract . . . . .	49
3.2	Introduction . . . . .	50
3.3	Literature Review . . . . .	51
3.4	System Characteristics . . . . .	54
3.5	Math Formulation . . . . .	55
3.5.1	Nomenclature . . . . .	55
3.5.2	State Variables . . . . .	57
3.5.3	Decision Variables . . . . .	57
3.5.4	Assumptions . . . . .	58
3.6	Problem Formulation . . . . .	58
3.6.1	System parameters . . . . .	59
3.6.2	Holding . . . . .	59
3.6.3	Skip-stops . . . . .	60
3.6.4	Short-turning . . . . .	62
3.6.5	Transfers . . . . .	64
3.6.6	Objective Function . . . . .	65
3.6.7	Constraints . . . . .	65
3.7	Model Optimization . . . . .	68
3.7.1	Optimization Framework . . . . .	68
3.7.2	Rolling Horizon . . . . .	69
3.7.3	Efficiency of the optimization process . . . . .	70
3.8	Simulation . . . . .	70
3.8.1	Simulation Framework . . . . .	70

3.8.2	Simulation Analysis . . . . .	71
3.9	Library of Tactic Frameworks: Combined Tactic-based Problem (CTP) . . . . .	72
3.10	Case Study . . . . .	73
3.10.1	Scenarios . . . . .	75
3.10.2	Control Strategies (Policy) . . . . .	75
3.10.3	Simulation Parameters . . . . .	76
3.11	Analysis . . . . .	77
3.12	Conclusions . . . . .	84
<b>4</b>	<b>Improved Reliability of Public Transportation Using Real-Time Transfer Synchronization</b>	<b>89</b>
4.1	Abstract . . . . .	89
4.2	Introduction . . . . .	90
4.3	Public Transport Service-Reliability Characteristics . . . . .	93
4.3.1	Real-time Situation Types-states . . . . .	93
4.3.2	Optimal Tactics . . . . .	95
4.3.3	Agent-based Modelling . . . . .	100
4.4	System Performance Indicator Model . . . . .	100
4.4.1	System Definition and Properties . . . . .	100
4.4.2	System Performance-indicator (SPI) Model . . . . .	103
4.5	Analysis of the Methodology . . . . .	105
4.5.1	Simulation Environment . . . . .	105
4.5.2	Simulation Analysis . . . . .	107
4.5.3	Framework of Analysis . . . . .	108
4.6	Case Study . . . . .	109
4.7	Results . . . . .	109
4.7.1	Sensitivity Analysis . . . . .	116
4.7.2	Computational Times . . . . .	117
4.8	Concluding Remarks . . . . .	118
<b>5</b>	<b>Real-time Public-Transport Operational Tactics Using Synchronized Transfers to Eliminate Vehicle Bunching</b>	<b>121</b>
5.1	Abstract . . . . .	121
5.2	Introduction . . . . .	122
5.2.1	Literature Review . . . . .	122
5.3	Control Methodology . . . . .	124
5.3.1	System Description . . . . .	124
5.3.2	Assumption . . . . .	124

5.3.3	Headway-based Model . . . . .	125
5.3.4	Direct Transfer (DT) . . . . .	127
5.3.5	Library of Tactics . . . . .	128
5.4	Simulation Experiments . . . . .	132
5.4.1	Event-activity System Modelling . . . . .	132
5.4.2	Simulation Environment . . . . .	133
5.5	Case Study . . . . .	133
5.5.1	Control Strategies(Policy) . . . . .	134
5.5.2	Simulation Analysis . . . . .	134
5.6	Analysis of the Results . . . . .	135
5.6.1	Average Waiting Times, Standard Deviations, and Bunching . . .	135
5.6.2	Headway Distribution . . . . .	138
5.6.3	Effectiveness of Performance . . . . .	139
5.6.4	Cycle Time Distribution . . . . .	140
5.7	Conclusions . . . . .	141
<b>6</b>	<b>Synchronized Transfers in Headway-Based Public Transport Service</b>	
	<b>Using Real-Time Operational Tactics</b>	<b>143</b>
6.1	Abstract . . . . .	143
6.2	Introduction . . . . .	144
6.3	System Control Models . . . . .	146
6.3.1	System Characteristics . . . . .	147
6.3.2	Headway-based Model Description . . . . .	147
6.3.3	Direct Transfer . . . . .	149
6.3.4	Holding Control Model . . . . .	152
6.3.5	Boarding-limit Control Model . . . . .	153
6.3.6	Skip-stop Control Model . . . . .	154
6.3.7	Additional Travel Time . . . . .	155
6.3.8	Problem Assumptions . . . . .	155
6.4	Simulation Analysis . . . . .	155
6.4.1	Event-Activity Process Modelling . . . . .	156
6.4.2	Simulation Environment . . . . .	157
6.5	Case Study . . . . .	157
6.5.1	Control Policy and Scenarios . . . . .	158
6.5.2	Simulation Analysis . . . . .	158
6.6	Analysis of Results . . . . .	159
6.6.1	Control Effectiveness . . . . .	160

6.6.2	Headway Distribution . . . . .	161
6.7	Conclusions . . . . .	161
<b>7</b>	<b>Energy Efficiency of Public Transport Systems Using Real-Time Control Method</b>	<b>165</b>
7.1	Abstract . . . . .	165
7.2	Introduction . . . . .	166
7.3	Methodology . . . . .	169
7.3.1	Real-time Control System . . . . .	169
7.3.2	Assumption . . . . .	171
7.3.3	Optimization Problem Formulation . . . . .	171
7.3.4	Environmental Impact . . . . .	174
7.3.5	LCA Framework . . . . .	175
7.4	Case Study . . . . .	176
7.5	Analysis and Results . . . . .	177
7.5.1	Analysis of TBC Model . . . . .	177
7.5.2	Analysis of Environmental Impacts . . . . .	179
7.6	Conclusion . . . . .	180
<b>8</b>	<b>Matching Public Transport Demand Using Tactic-Based Guidelines</b>	<b>183</b>
8.1	Abstract . . . . .	183
8.2	Introduction . . . . .	184
8.3	STAGE 1: Methodology and Findings of Users' Perception of The Service Factor . . . . .	187
8.3.1	Design of Questionnaire . . . . .	187
8.3.2	Data Collection and Survey Implementation . . . . .	188
8.3.3	Public Transport Service Factors and Application . . . . .	189
8.4	Decision Models . . . . .	189
8.4.1	Multinomial Logistic Regression Model . . . . .	191
8.4.2	The Decision Tree Model . . . . .	197
8.5	STAGE 2: Effects of Tactics on Users' Perception and Decision . . . . .	200
8.5.1	Operational Tactics . . . . .	200
8.5.2	Tolerated Time Model . . . . .	202
8.5.3	Results and Discussion . . . . .	212
8.6	Conclusions and Future Research . . . . .	213
<b>9</b>	<b>Public Transport Service-Quality Elements Based on Real-Time Operational Tactics</b>	<b>217</b>

9.1	Abstract . . . . .	217
9.2	Introduction . . . . .	218
9.3	Literature Review . . . . .	219
9.4	Attributes of Service Quality in advanced PT system . . . . .	221
9.5	Methodology . . . . .	223
9.5.1	Conjoint Analysis Instrument and Data Collection . . . . .	224
9.6	Results and Discussion . . . . .	225
9.6.1	Development of Conjoint Model . . . . .	226
9.6.2	Clustering the results . . . . .	228
9.6.3	Overall PT Service Satisfaction . . . . .	229
9.6.4	Discussion . . . . .	231
9.7	Conclusion and Remarks . . . . .	233
<b>10</b>	<b>Summary, Conclusion and Recommendations</b>	<b>235</b>
10.1	Summary of the Thesis . . . . .	235
10.2	Main Research Findings . . . . .	236
10.3	Limitations . . . . .	244
10.4	Future Research . . . . .	244
	<b>Bibliography</b>	<b>247</b>

# List of Figures

1.1	The proposed research process . . . . .	14
1.2	The proposed solution approach . . . . .	15
1.3	The general framework of the chapters . . . . .	16
2.1	Skip-Stop and Skip-Segment tactics . . . . .	29
2.2	Bus system and the study routes . . . . .	37
2.3	$\Delta TPTT$ with the two combined tactics . . . . .	43
2.4	Headway distribution . . . . .	45
2.5	Sensitivity of total passenger travel time . . . . .	46
3.1	Proposed PT system model . . . . .	55
3.2	A typical network snapshot . . . . .	58
3.3	CTP framework . . . . .	74
3.4	Auckland, NZ, bus system and study routes . . . . .	75
3.5	Total passenger travel time saved, and number of direct transfers . . . . .	85
3.6	Reduced and increased total passenger travel time . . . . .	86
3.7	Total passenger travel time saved . . . . .	86
4.1	States description . . . . .	102
4.2	System deterioration and repair . . . . .	102
4.3	An agent-based simulation modelling framework . . . . .	106
4.4	Time-State diagram at the control stop . . . . .	107
4.5	General analysis framework . . . . .	108
4.6	Bus system and the study routes, Auckland, New Zealand . . . . .	110
4.7	Effect of "No-Control" vs. "Holding-Skip-Stops" . . . . .	117
4.8	Effect of "Holding" vs. "Skip-Stops" tactic on SPI . . . . .	118
5.1	Space-time diagram of PT operations . . . . .	130
5.2	Headway distributions . . . . .	139
5.3	Headway means comparison . . . . .	140
5.4	Cycle time distribution . . . . .	141
6.1	Graphical representation of the PT network . . . . .	149
6.2	Flowcharts of EA simulation process . . . . .	156
6.3	Tactics effectiveness with two scenarios . . . . .	161
6.4	Headway distribution . . . . .	162
7.1	Overview of the methodology . . . . .	170
7.2	Life Cycle Assessment Framework . . . . .	174

7.3	Bus system and the study routes . . . . .	177
7.4	Global warming potential . . . . .	179
8.1	Assessment of service factors . . . . .	190
8.2	Impact of independent variables on passengers' decisions, Case1 . . . . .	198
8.3	Impact of independent variables on passengers' decisions, Case2 . . . . .	199
8.4	Decision-tree output of passengers' decisions . . . . .	201
8.5	Extra Time tolerated by Users without a Bonus . . . . .	214
8.6	Extra Time tolerated by Users with a Bonus . . . . .	215
9.1	Importance index of SQ factor identified clusters . . . . .	230
9.2	Satisfaction with the overall reliability of PT service . . . . .	232
10.1	The main contribution of each chapter . . . . .	243



# List of Tables

1.1	The main components of the library of tactics . . . . .	4
1.2	Classification of previous research . . . . .	5
2.1	Results of Optimization at Transfer-point1 . . . . .	40
2.2	Direct Transfers for each scenario . . . . .	41
3.1	List of scenarios . . . . .	76
3.2	Route characteristics . . . . .	77
3.3	Matrix of transfer points . . . . .	77
3.4	Summary of the results . . . . .	78
3.5	Main simulation results . . . . .	80
4.1	State of vehicle with possible tactics . . . . .	103
4.2	Disutility function for related tactic . . . . .	105
4.3	Results of performance indicators . . . . .	111
5.1	Route characteristics . . . . .	135
5.2	Service performance under two scenarios . . . . .	137
6.1	Simulation scenarios . . . . .	158
6.2	Summary of the results . . . . .	159
7.1	PT system performance . . . . .	178
8.1	List of scenarios . . . . .	191
8.2	Results of Independence Tests . . . . .	193
8.3	Results of Independence Tests . . . . .	196
8.4	Independent Variables of the MLR Model . . . . .	203
8.5	MLR Model of Tolerated Holding Time . . . . .	206
8.6	MLR Model of Time Tolerated for the Skip-Stops Tactic . . . . .	209
8.7	Results of Average Extra Time Tolerated . . . . .	213
9.1	Situational components employed in the conjoint analysis . . . . .	225
9.2	Utility and importance index of the SQ element . . . . .	226
9.3	Cluster results for Cases 1 and 2. . . . .	229



# List of Abbreviations

<b>ABS</b>	<b>A</b> gent- <b>B</b> ased <b>S</b> imulation
<b>APC</b>	<b>A</b> utomatic <b>P</b> assenger <b>C</b> ounting
<b>AT</b>	<b>A</b> uckland <b>T</b> ransport
<b>ATT</b>	<b>A</b> dditional <b>T</b> ravel <b>T</b> ime
<b>AVL</b>	<b>A</b> utomatic <b>V</b> ehicle <b>L</b> ocation
<b>CBD</b>	<b>C</b> entral <b>B</b> usiness <b>D</b> istrict
<b>CP</b>	<b>C</b> onstraint <b>P</b> rogramming
<b>CTP</b>	<b>C</b> ombined <b>T</b> actic-based <b>P</b> roblem
<b>CV</b>	<b>C</b> oefficient of <b>V</b> ariation
<b>DP</b>	<b>D</b> ynamic <b>P</b> rogramming
<b>DT</b>	<b>D</b> irect <b>T</b> ransfer
<b>E</b>	<b>E</b> arliness
<b>EA</b>	<b>E</b> vent <b>A</b> ctivity
<b>FIFO</b>	<b>F</b> irst <b>I</b> n <b>F</b> irst <b>O</b> ut
<b>GHG</b>	<b>G</b> reen <b>H</b> ouse <b>G</b> as
<b>GPS</b>	<b>G</b> lobal <b>P</b> ositioning <b>S</b> ystem
<b>GTFS</b>	<b>G</b> eneral <b>T</b> ransit <b>F</b> eed <b>S</b> pecifications
<b>GWP</b>	<b>G</b> lobal <b>W</b> arming <b>P</b> otential
<b>H-BL</b>	<b>H</b> olding and <b>B</b> oarding- <b>L</b> imit
<b>H-S</b>	<b>H</b> olding and <b>S</b> kip-stop
<b>H-SC</b>	<b>H</b> olding and <b>S</b> peed- <b>C</b> hange
<b>H-SH</b>	<b>H</b> olding and <b>S</b> hot- <b>T</b> urning
<b>H-SS</b>	<b>H</b> olding and <b>S</b> kip- <b>S</b> egment
<b>ITS</b>	<b>I</b> ntelligent <b>T</b> ransportation <b>S</b> ystem
<b>IVC</b>	<b>I</b> nter <b>V</b> ehicles <b>C</b> ommunication
<b>LCA</b>	<b>L</b> ife <b>C</b> ycle <b>A</b> ssessment
<b>LT</b>	<b>L</b> ibrary of <b>T</b> actics

<b>MIP</b>	<b>M</b> ixed <b>I</b> nteger <b>P</b> rogramming
<b>MLR</b>	<b>M</b> ultinomial <b>L</b> ogistic <b>R</b> egression
<b>MST</b>	<b>M</b> aximal <b>S</b> ynchronized <b>T</b> imetable
<b>NA</b>	<b>N</b> ot <b>A</b> vailable
<b>NP</b>	<b>N</b> on- <b>P</b> olynomial
<b>OD</b>	<b>O</b> rigin <b>D</b> estination
<b>OPL</b>	<b>O</b> ptimization <b>P</b> rogramming <b>L</b> anguage
<b>OSM</b>	<b>O</b> pen <b>S</b> treet <b>M</b> ap
<b>PT</b>	<b>P</b> ublic <b>T</b> ransport
<b>SD</b>	<b>S</b> tandard <b>D</b> eviation
<b>SE</b>	<b>S</b> tandard <b>E</b> rror
<b>SPI</b>	<b>S</b> ystem <b>P</b> erformance- <b>I</b> ndicator
<b>SQ</b>	<b>S</b> ervice <b>Q</b> uality
<b>T</b>	<b>T</b> ardiness
<b>TBC</b>	<b>T</b> actic- <b>B</b> ased <b>C</b> ontrol
<b>TPTT</b>	<b>T</b> otal <b>P</b> assenger <b>T</b> ravel <b>T</b> ime

# List of Symbols

$A_r^n$	Vehicle arrival time of route $r$ at stop $n$
$a_r^n$	The number of alighting passengers of route $r$ at stop $n$
$B_r^n$	The number of passengers for a vehicle departing stop $n$ on route $r$
$b_r^n$	The number of boarding passengers of route $r$ at stop $n$
$BL_{n,r}$	Vehicle boarding limit of route $r$ at stop $n$ ; if stop boarding limited=1, otherwise=0
$c_r^n$	Vehicle running time of route $r$ at stop $n$ from the previous stop
$D_r^n$	Vehicle departure time of route $r$ at stop $n$
$d_r^n$	Vehicle dwell time of route $r$ at stop $n$ (in seconds)
$E_r^I$	vehicle elapsed time on route $r$ from the previous stop to the current position at segment $I$
$g_{k,n,r}$	The number of passengers prevented to board vehicle trip $k$ at stop $n$ on route $r$
$h_r$	Vehicle headway of route $r$
$HO_r^n$	Vehicle holding time of route $r$ at stop $n$
$k_r^I$	Positional stop for a snapshot at segment $I$ on route $r$
$l_r^n$	Passengers' load of route $r$ at stop $n$
$m_r$	Maximum total number of stops of route $r$
$N$	Set of stops, in which $n \in N$
$p_{r\acute{r}}^n$	The number of transferring passengers of route $r$ to route $\acute{r}$ at stop $n$
$Q_r^{max}$	Passenger capacity of vehicle of route $r$
$q_{k,n,r}$	The number of passengers skipped and should wait for the next vehicle to bring them to their destination from vehicle trip $k$ at stop $n$ on route $r$
$R$	Set of routes in which $r, \acute{r}, x \in R$
$S$	Set of all possible states of the system
$s_{k,r}$	The spacing between vehicle $k$ and $k - 1$ on route $r$
$\bar{s}_{k,r}$	The desired space between vehicle $k$ and $k - 1$ on route $r$
$S_r^n$	Bus skipping stop of route $r$ at stop $n$ ; if stop skipped= 1, otherwise= 0

$SH_r^n$	Vehicle short-turning stop at stop $n$ on route $r$ ; if stop short-turn= 1, otherwise= 0
$T_r$	Vehicle schedule deviation of route $r$
$TF$	Set of all transfer points, in which $tr \in TF$
$TP_r^{tr}$	Transfer stop of route $r$ at transfer point of $tr$
$u_F$	Disutility function
$U_r$	Last transfer stop on route $r$
$W_r^n$	Number of passengers waiting at stops further along route $r$ and stop $n$ (future passengers)
$WT_r^n$	Extra waiting time per passenger at previous stops as a result of the applied tactics
$x_{k,r}$	The position of bus $k$ at time $t$ on route $r$
$Y_{rr'}^n$	Possible transferring from route $r$ to route $r'$ at transfer stop $n$ , pre-tactics; if a possible transfer occurs= 0, otherwise= 1
$Z_{rr'}^n$	Possible transferring from route $r$ to route $r'$ at transfer stop $n$ , post-tactics; if a possible transfer occurs= 0, otherwise= 1
$\alpha$	The bus-situation index
$\beta_{(i,j)}$	The recovery of the system between states $i$ and $j$
$\Gamma_r^n$	Time to reach a desired stop skipped of route $r$ at stop $n$
$\gamma_r^n$	The number of passengers who wish to have transfers at transfer points with respect to route $r$ and stop $n$
$\gamma_{(i,j)}$	The system deterioration rate between states $i$ and $j$
$\gamma_{n,r}$	A dimensionless measure of the demand rate at stop $n$ on route $r$
$\lambda_r^n$	Passenger arrival rate at stop $n$ on route $r$
$\nu_r^n$	Passengers alighting rate at stop $n$ on route $r$
$\nu_{k,n,r}$	The speed of vehicle $k$ at stop $n$ on route $r$
$\nu_{k,n,r}^c$	The control speed of vehicle $k$ at stop $n$ on route $r$
$\nu_{k,n,r}^d$	The desired speed of vehicle $k$ at stop $n$ on route $r$
$\Omega(t)_r^n$	Time penalty function of route $r$ at stop $n$
$\omega$	Ratio between the average speed of a bus and the average walking speed of pedestrian (same ratio for all routes and stops)
$\sigma^2(h_{k,n,r})$	variance of headway for a given vehicle trip $k$ at stop $n$ on route $r$
$\theta_r^I$	Vehicle schedule deviation at segment $I$ on route $r$

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$\xi_{k,n,r}$	The deviation of the headway for a given vehicle trip $k$ from the desired headway at stop $n$ on route $r$
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Arguably, the use of public transport (PT), being accountable for only a fraction of the total emissions, can help make transportation more green, and economical. However, in terms of reliability and efficiency, environmental impacts, and users' behaviours, PT itself has great potential for improvement. A PT system usually operates within a complex urban area where small scale shocks of its operation may results in large-scale disruptions to passengers and PT agencies. This includes increased journey times, which lead to economic (Caragliu et al., 2011), social (Banister and Berechman, 2001), and environmental (IEA, 2009) impacts. A recent study in the UK shows that 23% of travel time is missed in connections for trips with more than one mode, and that the lack of synchronization has contributed to decrease in patronage by the population (Gallotti and Barthelmy, 2014). Therefore, a common strategy implemented internationally by PT agencies is to develop an integrated, multi-modal transport system in order to provide travellers with a viable alternative to private cars.

An important element for retaining existing users and attracting new passengers is to improve serviceability by offering routes with "seamless" transfers. Ceder (2007, 2015) defined:

*"A well-connected transit path as an advanced, attractive transit system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, part of the door-to-door passenger chain".*

Thus, the question arises as to what can be done to increase the PT serviceability and reliability, to reduce passengers' frustration especially in transfer points, and to decrease the environmental impact in a daily PT system operation. Answer to this question will certainly make the PT service more attractive, efficient, and thus, will encourage people to leave their car at home and use the PT service.

## 1.2 Background and Significance of the Research

Principally, one of the most challenging problems of transportation planning is how to shift a significant number of car users (who consume the highest percentages of the energy used for transportation) to PT in a sustainable manner. Findings show that in order to increase PT usage, the service should be considered in a way that provides

the levels of service required by passengers and by doing so, attract potential users (Hadas and Ceder, 2008, Nesheli and Ceder, 2015b).

Service reliability in PT operations giving a significant attention as agencies become faced more and more with the immediate problem of providing credible service while attempting to reduce operating costs. Unreliable service has been considered as the major restrictive factor to current and prospective passengers (Hadas and Ceder, 2010a). Balcombe et al. (2004), in a practical UK transit guide, report that in passengers' perception, the service reliability of local bus services is considered twice as important as frequency.

PT service reliability problems can be categorized into two groups: "environmental" and "inherent" (Abkowitz, 1978). The first group includes such factors as traffic signals, changes in traffic conditions, variation in demand, and availability of crew and vehicles on any given route and day. The second group consists of setting and distribution of waiting times, boarding and alighting times, transfer times, headways and travel times on any given route and day. Accordingly, they classified reliability-improvement strategies as preventive and corrective/restorative. Ceder (2007, 2015) argued that some causes of unreliable service are chronic and known in advance; proper planning and adjustments can address these causes. Other causes are unpredictable in nature (i.e., random events) and require real-time responses, preferably taken from a library of tactics. The main components of the library of tactics are illustrated in a Table 1.1.

Several studies have focused on implementing real-time control actions. As summarized in Table 1.2, various mathematical modelling and optimization methods have been employed to solve the real-time control problems. These studies differ in methods, types and conditions of tactics and strategies that are applied.

**Table 1.1:** The main components of the library of tactics

Type of Tactics	Description of Implementation
Holding the vehicle	This tactic can be used for improving on-time performance, eliminating bunching, and responding to unexpected demand; however, it has an adverse effect on on-board passengers.
Skip-stop/segment	When a vehicle is behind schedule the skip-stop operation can be utilized to pass stops at which no passenger wishes to alight; however, it has an adverse effect on waiting passengers at those stops.
Changes in speeds	Can improve on-time performance, regulate headway and eliminate bunching; in the slowing-down cases, it may be better valued by the on-board passengers than is the holding strategy; however it is very challenging to implement in practice.
Deadheading and short-turning	Can be used as corrective actions for unforeseen situations such as unexpected demand or any operational shocks.
short-cut and express	The local service can convert to short-cut or express if it accommodates the destinations of all on-board passengers.
Boarding-limit	In case of a route in high demand, and in order to improve the performance of the service, a boarding-limit tactic can be applied to regulate the vehicle headway or schedule deviation.
Reserve vehicle and leapfrogging	To improve the serviceability of the operation, these tactics can be used. Employing a reserve vehicle as a real-time supportive action is suitable in situations where unexpected demand may occur. Finally, in order to rectify a load-imbalance scenario between two following vehicles, and prevent bunching, the leapfrogging operation can be utilized.

Table 1.2: Classification of previous research related to real-time control method

Reference	Method	Strategy/Tactic	Description
Osuna and Newell (1972)	Dynamic programming	Holding	The problem of optimal control for an idealized PT system is investigated. Minimizing the average wait time was the objective function.
Barnett (1974)	A heuristic algorithm	Holding	A simple holding strategy applied to reduce headway variations due to operational randomness on the PT routes. The objective function was minimizing average passenger wait times including stop and ride times.
Turnquist and Blume (1980)	Screening , a theoretical analysis	Holding	The work focuses on measuring the headway variability and the proportion of total passengers who will be delayed as a result of a holding strategy.
Abkowitz and Lepofsky (1990)	Experimental	Holding	The feasibility of implementing headway-based holding strategies apply to high-frequency PT routes in the field has been investigated. Minimization of total waiting time was the objective function.

Eberlein et al. (1999, 2001)	A nonlinear quadratic program; heuristic algorithm	Deadheading, Expressing, and Holding	Efficient algorithms are advanced for solving the control models. The advantages, disadvantages, and conditions for each type of control strategy are considered. The objective function was to minimize the total passenger waiting time. The results showed that the effectiveness of combined control is higher than any single type of control.
Hickman (2001)	Optimization (convex quadratic programming)	Holding	A stochastic holding model at a given control station is presented. The author showed how the model can be applied to attain a significant reduction in passenger waiting time.
Dessouky et al. (1999, 2003)	Simulation	Holding	Control strategies that depend on technologies using ITS compared with those that depend only on local information (e.g., time that a bus arrived at a stop).
Fu and Yang (2002)	Simulation	Holding	Two holding control models have been investigated. The results showed that If applicable, holding control should be applied to two points along the route, one preferably at the terminal and the other at a high-demand stop near the middle of the route.

Zhao et al. (2003)	Heuristic, simulation	Holding	A distributed control approach based on multiagent negotiation algorithm is developed. The objective function consisted of two types of waiting costs: off-bus and on-bus costs.
Zolfaghari et al. (2004)	Heuristic, simulated annealing	Holding	The objective function was to minimize the waiting time of passengers at all stops on that route. They concluded that beside the holding tactics other control strategies should be developed and applied.
Sun and Hickman (2005)	Optimization (Nonlinear integer programming), simulation	Skip-stop	The skip-stop tactic using in a real time manner has been formulated. The authors developed a deterministic modelling framework.
Yu and Yang (2009)	SVM, GA	Holding	A dynamic holding strategy in PT system with real-time information considered. In order to determine the optimal holding times, a GA model aiming to minimize the user costs is constructed.
Daganzo (2009) and Daganzo and Pilachowski (2011)	Adaptive control scheme	Speed-change, Holding	Strategies to increase the efficiency of a high frequency PT route were studied. The suggested model dynamically determines bus holding times at route control points based on real-time headway information.

Hadas and Ceder (2010a)	Dynamic programming, simulation	Holding, skip-stops	<p>The objective function was minimizing the total travel time. A fast and efficient distributed DP heuristic model has been developed.</p>
Cortés et al. (2011)	Hybrid predictive control, GA	Holding, skip-stop	<p>A multi-objective optimization based on minimization of waiting time and impact of strategies was developed. The objective function sought to generate better operational decisions under uncertain demand at bus stops.</p>
Cats et al. (2011)	Simulation	Holding	<p>A dynamic transit-simulation model, Bus Mezzo, is proposed. They considered the interaction of passenger activity, transit operations, and traffic dynamics in their model.</p>
Delgado et al. (2012)	Optimization (non-linear and not convex), simulation	Holding, Boarding-limit	<p>A mathematical model without binary variables was proposed for real-time transit operations. The objective function was to minimize the total travel time of all passengers.</p>
Van Oort et al. (2012)	A theoretical analysis	Holding	<p>The study investigated schedule-based holding strategy with timetable adjustment strategy on long-headway transit lines.</p>
Ji and Zhang (2013)	Quadratic static optimization program, simulation	Holding	<p>A robust dynamic control strategy to regulate bus headways and to prevent buses from bunching by holding them at bus stops is proposed.</p>

Chen et al. (2013)	Heuristic, simulation	Holding	The study developed a control strategy of holding a group of buses at a single or multiple control point(s). The problem considered as a non-convex optimization problem with linear constraints which minimizes the total passenger waiting time both on-board and at stops in high frequency bus service lines.
Ceder et al. (2013b)	Optimization, simulation	Holding, skip stop	The model determines the impact of instructing vehicles to either hold at or skip certain stops, on the total passenger travel time and the number of simultaneous transfers.
Muñoz et al. (2013)	Hybrid predictive control and deterministic optimization	Holding	A comparison study between the deterministic approach and the hybrid predictive control approach is conducted. The results indicate that the deterministic approach operates better under scenarios in which bus capacity is reached frequently along the route while the hybrid predictive control approach performs better in situations where this does not happen.



Liu et al. (2014)	Optimization	Speed-change, Holding	An inter-vehicle communication (IVC)-based scheme to optimize the synchronization of planned transfers in PT networks is developed. A semi-decentralized control strategy was advanced for the IVC systems to make the optimization a parallel process.
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Note: SVM= Support vector machine; GA= Genetic algorithm; DP= Dynamic programming.

While there is an extensive research conducted to analyse PT movements at a single control point, there are only a few analytical studies dealing with real-time control issues especially in a complex PT network with a combination of various tactics. There were no systematic analyses of real-time control until Daganzo (2009) proposed headway control at certain control points. Besides, there is need to assess the effect of applying these real-time tactics in a proper study of environmental side and demand side perceptions and decisions as complementary to the agent side. It is believed that the proposed concept will reduce the uncertainty of PT vehicle arrival time to a transfer point, and by deploying certain combinations of tactics; library of tactics, (e.g., hold, skip-stop, speed-change, short-turn, short-cut, etc.) to enable increasing of the number of direct transfers and reducing the total travel time. Thus the concept has large potential for increasing the efficiency and attractiveness of PT networks involved with planed transfers. Given these benefits, there is the real potential for the proposed model to be deployed in real life, providing a major advantage for PT operators, policy-makers and PT users.

### 1.3 Research Problem

Fundamentally there are two distinctive real-time PT performance disruptions: (1) deviations from the schedule (timetable), but not necessarily creating an imbalance between supply and demand; (2) creation of an imbalance between supply and demand (overloaded and almost empty vehicles), but not necessarily deviating from the schedule (Ceder, 2007, 2015). Given that these disruptions are known in real-time (e.g., by an automatic vehicle location (AVL) data collection systems and GPS), corrective and restorative control strategies can take place.

Various studies have been advanced to model PT real-time control (Delgado et al., 2013, Hadas and Ceder, 2010a, Hanaoka and Qadir, 2009, Hickman, 2001, Sun and Hickman, 2005). However, the main drawback of possible real-time control actions is the lack of prudent modeling and software that can activate these actions, whether automatically, semi-automatically, or manually. In addition, it has been very difficult to evaluate the positive and negative effects of individual control strategies with respect to operations and passenger travel times under complex network and real-world conditions (Carrel et al., 2013). Such modeling can be employed in a PT control center in order to allow for the best exploitation of real-time information. Thus, the following key questions arise as:

(i) how modelling and simulation can be created to optimally select control actions such as tactics for real-time operations deployment using the stochastic nature of PT networks? (ii) How do users benefit from the use of real-time information, including real-time control actions? And (iii) how effective is the model at reducing environmental impacts? The present research proposes a methodology, based on a real-time framework, to find the optimal combination of tactics for controlling the PT system. The objective is to develop intelligent modeling with a "*Library of Tactics*" in terms of real-time control actions; these developments will be based on optimization and simulation frameworks.

## 1.4 Scope of Research and Objectives

A PT system has two major phases: planning and operation. The first phase aims at designing routes; time tables, synchronized transfers, and timed transfers that improve the planned transfers on the basis of a priori data (Ceder, 2007, 2015). Synchronized transfer studies are described by Wirasinghe and Liu (1995) and Ceder and Tal (2001), and the timed-transfer concept is described by Maxwell (1999). The second phase aims at improving PT service reliability using real-time data. Therefore, the question arises as to whether remedies exist to service reliability problems and, if so, whether they are implementable and comprehensive. The present research assumes that planned transfers exist (as part of the first phase); however, with a continuous flow of real-time data, there is need to select tactics that will attain the minimum discrepancy between planning and operations.

The research investigates and explains the selection of the best conjunction of different tactics and their effect on environmental factors, and travellers' behaviours. The overall aim of the research is to develop a library of tactics for PT real-time operations to attain optimal combination of tactics and strategies for reducing the total passenger travel time and increasing the number of direct people transfers (without wait) at designated locations. The modelling is based on optimization and simulation frameworks. Following are the specific objectives:

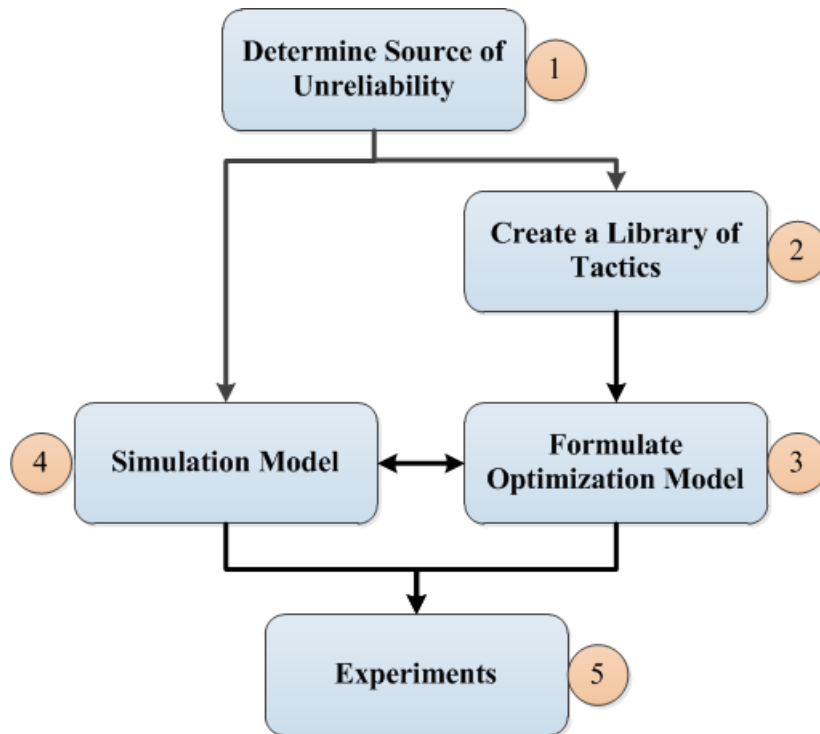
- (i) Constructing an optimization framework to comply with the research's goal such that it will reflect and combine the perspectives of the three main players of the problem: the user, the operator, and the community (government).

- (ii) Creating a simulation framework for the validation of the optimal results and as a tool for sensitivity analysis of combinations of tactics to attain maximum PT productivity and efficiency.
- (iii) Developing a model that can be used in real-time operations to achieve efficient interaction between the optimization and simulation procedures with the purpose of reducing the total passenger travel time and increasing the number of direct transfers.
- (iv) Testing the modelling developed on case studies for the examination of the procedure developed.
- (v) Establish guidelines on the best approaches to use online to increase the probability of direct passenger transfers and, at the same time, minimizing the total passenger travel time.
- (vi) Developing an efficient and environmentally sustainable method for policymakers to operate PT networks through the use of operational tactics.
- (vii) Developing a qualitative and quantitative study of PT users to obtain a deeper understanding of travellers' attitudes toward transport uncertainty and to explore perceptions of real-time operational tactics on PT service quality.

## 1.5 Research Methodology

The appearance of new information and communication technologies, such as GPS and automatic vehicle location (AVL) systems, have made possible the development of more complex control schemes. In addition, using intelligent and high-resolution real-time passenger-information systems allow to improve the daily implementation of these operational tactics. High-resolution information lends the travellers a sense of greater control over their trip.

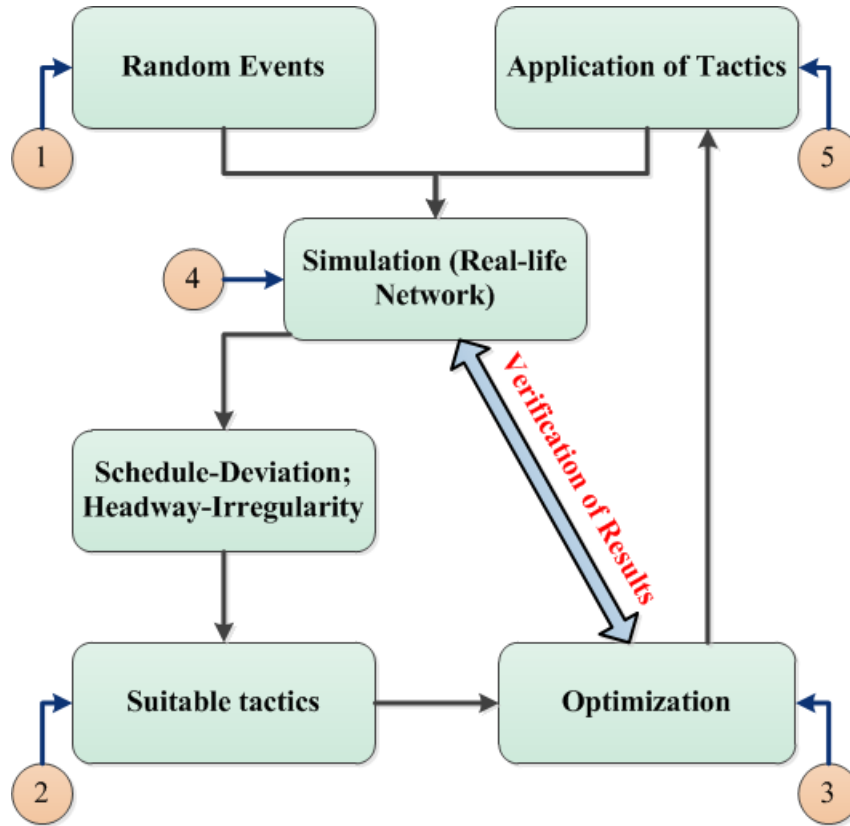
The input to the analysis will be based on real-time automatic data-collection systems used in PT operations, such as AVL, automatic passenger counter (APC), automatic fare payment (AFP) and computer-aided dispatch (CAD). Currently transit agencies follow the General Transit Feed Specification (GTFS) for route and schedule information and connect GTFS real-time data to AFC and APC systems. Tactics embodies in simulation



**Figure 1.1:** The proposed research process for developing real-time operational tactics.

and statistical models will be developed to predict delays and disruption, to be compared with actual delays and disruptions. Consequently, a set of possible control strategies will be developed from which an optimal strategy can be selected. The development will enable the selection of best tactics and strategies for deployment in real-time situation so as to maintain reliable PT service including synchronization between vehicles.

Generally the methodology developed in operational side utilizes simulation (with the case study input), optimization and again simulation runs with the outcome of the deterministic optimization for validation under a stochastic framework. When the optimization program recommends tactics to deploy in the simulation, it is possible to evaluate the estimated percent/proportion of direct transfers with tactics (based on the optimization model projection); in addition also to find out how often the direct transfer is actually attained under stochastic conditions. This approach is used and entitled '*optimization&simulation-based*' as opposed to the results of the optimization only entitled '*optimization-based*'. Figure 1.1 illustrates the complete process of first part of the research which is the main part of the research and Figure 1.2 depicts the proposed solution approach to solve the problem based on each step.

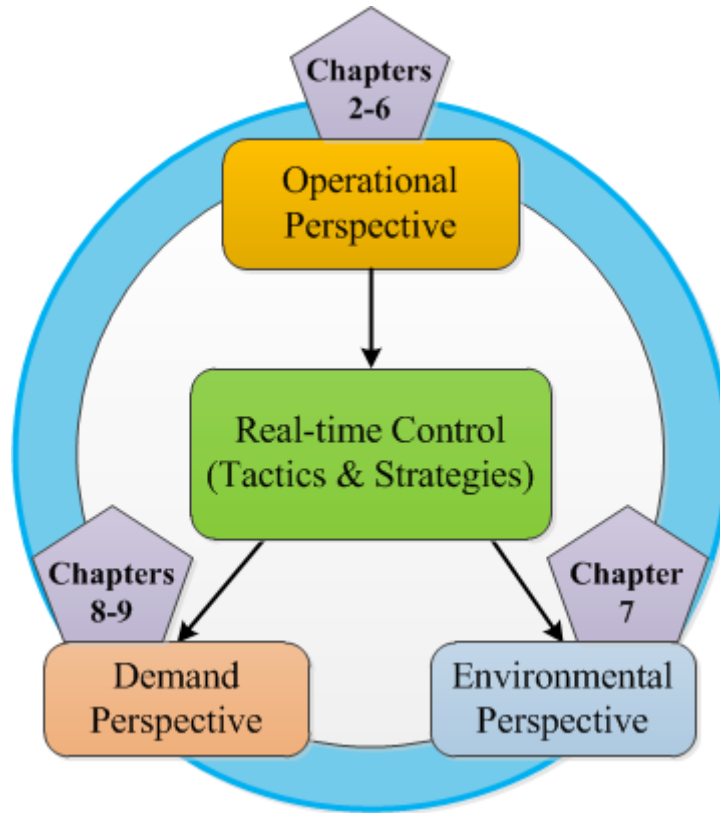


**Figure 1.2:** The proposed solution approach (Methodology) with reference to input steps of Figure 1.1.

The following section provides more information on the general framework of the research, including environmental impacts and users' perception toward applying the library of tactics.

## 1.6 Thesis Outline

The outline of the thesis consists of assembly of eight journal papers (Nesheli and Ceder, 2014, 2015a,b, 2016, Nesheli et al., 2015a,c,d,e) seeking to address the objectives stated in Section 1.4; this base of the thesis is complemented by additional four chapters of introduction, summary of findings, discussion and conclusions. Evidently, some repetition of material among the chapters was inevitable. **Chapter 2 to 9** are grouped into three main categories: operational, environmental and demand. All these chapters appear in the form they were either accepted for publication or in-review as it was submitted for publication with some minor format changes. **Chapter 10** is the summary of findings,



**Figure 1.3:** The general framework of the chapters and the overall aim of the research.

discussion and conclusion of the research. Figure 1.3 illustrates the general framework of the chapters and the overall aim of the research.

An overview and key deliverables of **Chapter 2** to **10** are presented as follow.

*Chapter 2: Optimal combinations of selected tactics for public-transport transfer synchronization.*

The main aim of this chapter is to develop a library of selected tactics based on optimization and simulation approach. A mathematical programming model was formulated to determine the impact of instructing vehicles to either "*hold*" at or "*skip certain stops/segments*" on the total passenger travel time and the number of simultaneous transfers. The results showed that considering the skip-segment by formulating penalty functions for disadvantaged passengers yielded better results than skipping individual stops. The methodology of work commences by the use of TransModeler simulation tool Caliper (2013) to represent a real-life example and to generate random input data for the proposed optimization model. Then standard optimization software, ILOG IBM (2012), is used to solve optimally a range of different scenarios determined by the simulation runs.

*Chapter 3: A Robust, Tactic-Based, Real-Time Framework for Public-Transport Transfer Synchronization.*

The main purpose of this chapter is to develop a novel robust tactic-based real-time framework to increase the likelihood of PT transfer synchronization. Despite the contribution of [Chapter 2](#), the proposed approach had some limitations, mainly related to the assumptions used for constructing the model such as the assumptions associated with passenger demand i.e., passenger demand is independent of vehicle arrival time. This chapter continues, rectifies the limitations and advances the research of [Chapter 2](#) by introducing a new operational tactic, "*short-turn*". To the author's knowledge, the present chapter provides the formulation and implementation of the short-turning tactic as a real-time control action for the first time in the literature. A hybrid model that uses mixed integer programming (MIP) and constraint programming (CP) techniques to solve the problem is proposed. An agent-based simulation framework is also used to represent real-life scenarios, generate random input data, and validate the optimization results.

*Chapter 4: Improved Reliability of Public Transportation Using Real-Time Transfer Synchronization.*

The aim of this chapter is to assess and improve service reliability by presenting a proper performance indicator that quantifies the level of system efficiency. In previous chapters the methods of implementing real-time operational tactics are developed. In this chapter, using system reliability theory, a new PT performance index and deterioration and improvement patterns to improve reliability of PT in real-time is proposed. Five types of vehicle positional situations with reference to a transfer point, in order to investigate the efficiency level of the PT system are considered. An agent-based modelling for simulation is used to incorporate more prudent condition of real-life scenarios. In order to understand the importance of each components of the developed system performance index model, a decision tree-based method was used.

*Chapter 5: Real-time Public-Transport Operational Tactics Using Synchronized Transfers to Eliminate Vehicle Bunching.*

In this chapter one of the most irritating phenomena in urban PT operations, called "bunching" or "pairing" is addressed. The main purpose of this chapter is to develop a methodology, using simulation, to attain optimally real-time control tactics so as



to minimize the bunching phenomenon. An event-activity based, transport-simulation framework is developed to represent a real-life example to evaluate the proposed theoretical model. In this study the library of tactic is constructed based on "*Speed-change*" and "*Holding the vehicles*" control model.

*Chapter 6: Synchronized transfers in headway-based public transport service using real-time operational tactics.*

In terms of head-based real-time control, and following the previous chapter a real-time tactic-based control (TBC) procedure to increase the service reliability and actual occurrence of synchronized transfers in headway-based PT system is presented in this chapter. The procedure aims at minimizing, for passengers, additional travel times and reducing the uncertainty of meetings between PT vehicles. The TBC utilizes selected online operational tactics, such as "*holding*", "*boarding limit*", and "*skip-stops*", all of which are based on real-time data.

*Chapter 7: Energy efficiency of public transport systems using real-time control.*

This chapter investigates and analyses the benefits of using real-time PT operational tactics in reducing the undesirable environmental impacts. The method is developed in two phases: : (1) constructing a real-time PT tactic-based control system using three tactics: "*holding*", "*skip-stops*", and "*boarding limit*", (2) designing a life cycle assessment process to evaluate the environmental impacts of the PT system before and after the operational use of real-time operational tactics.

*Chapter 8: Matching Public Transport Demand Using Tactic-Based Guideline*

This chapter investigates the effect of implementing real-time tactics on passengers' perceptions and decisions (the demand side) as complementary to the agent side. The main objective of this chapter is to provide PT agencies a guideline on demand control. An experimental user preference survey is conducted to determine users' perception and decisions related to various operational tactics. To evaluate the differences, the same survey was conducted in two cities with different characteristics: Auckland in New Zealand and Lyon in France. A statistical analysis was carried out, and decisions models were built using both multinomial logistic regression and a decision-tree-based method.

*Chapter 9: Public Transport Service-Quality Elements Based on Real-time Operational Tactics.*

The purpose of this chapter is to identify an understanding of what constitutes PT service quality (SQ) at the operational level, using real time operational tactics based on user-centric performance measures. A conjoint analysis combined with cluster analysis is developed to capture the most important factors in evaluating the SQ process.

*Chapter 10* Summary of findings, conclusion and recommendations.

This chapter summarizes the finding and conclusion, addresses the key research contributions, and finally identifies directions for future research.



## Chapter 2

# Optimal Combinations of Selected Tactics for Public-Transport Transfer Synchronization

*Published in:*

*Transportation Research Part C: Emerging Technologies.* **48**, 491-504.

(Nesheli and Ceder, 2014)

### 2.1 Abstract

Handling efficiently and effectively real-time vehicle control is of major concern of public transport (PT) operators. One related problem is on how to reduce the uncertainty of simultaneous arrivals of two or more vehicles at a transfer point. Improper or lack of certain control actions leads to have missed transfers, one of the undesirable features of the PT service. Missed transfers result in increase of passenger waiting and travel times, and of passenger frustration. This work focuses on reducing the uncertainty of missed transfers by the use of control tactics in real-time operation. The developed model improves the PT service performance by optimally increasing the number of direct transfers and reducing the total passenger travel time. This model consists of two policies built upon a combination of two tactics: holding and skip-stop/segment, where a segment is a group of stops. The implementation of the concept is performed in two

steps: optimization and simulation. The optimization searches for the best combination of operational tactics. The simulation serves as a validation of the optimal results under a stochastic framework. A case in Auckland, New Zealand is used. The results show that by applying the holding-skip stop, and holding-skip segment tactics the number of direct transfers are increased by about 100% and 150%, and the total passenger travel time is reduced by 2.14% and 4.1%, respectively, compared with the no-tactic scenario. The holding-skip segment tactic results with 47% more direct transfers than the holding-skip stop tactic for short headway operation.

## 2.2 Introduction

The lack of a prudent real-time transit control system is of major concern of public transport (PT) operators. Improper or lack of certain control actions leads to have missed transfers, one of the undesirable features of the PT service. Missed transfers results in increase of passenger waiting and travel times, and of passenger frustration.

A recent study by Ceder et al. (2013b) investigates how to use selected operational tactics in PT networks for increasing the actual occurrence of scheduled transfers. Their model determines the impact of instructing vehicles to either hold at or skip certain stops, on the total passenger travel time and the number of simultaneous transfers. While there is an extensive research conducted to analyze PT movements at a single control point, there are only a few analytical studies dealing with real-time control issues. Newell (1974) and Barnett (1974) demonstrate that a bus falling slightly behind schedule tends to pick up more passengers causing it to slow down until it eventually bunches with a trailing bus. Though the bunching could be eliminated to some extent by slowing down the trailing bus, this will lead to an increased travel time of the passengers onboard this bus.

Turnquist and Blume (1980), in a study on holding tactics, identify conditions under which those tactics are effective. They implement a simple screening model to assess the effectiveness of control policies. Their work focuses on measuring the headway variability and the proportion of total passengers who will be delayed as a result of a holding strategy. Li et al. (1992) focused on developing bus dispatching criteria at various stops. Based on proposed cost functions, a holding and stop skipping criterion is analyzed and optimized. They consider a single route, not taking into account transfers and

transit centers. Their study shows that a tight stop skipping control strategy significantly increases the average waiting time, whereas the most critical decision variable is the holding control parameter. Generally speaking, and following Eberlein et al. (1999), control strategies can be divided into three categories: stop control, inter-stop control, and others. The first category contains two main classes of strategies which are known as holding and stop skipping. The second - includes speed control, traffic signal preemption, etc. The third - consists of strategies such as adding vehicles, splitting trains, and more. In a follow up study and as an inclusive analytical investigation in vehicle holding strategy Eberlein et al. (2001) formulate the holding problem as a deterministic quadratic program and develop an efficient solution algorithm to solve it. At the same time Hickman (2001) presents a stochastic holding model at a given control station; a convex quadratic program with a single variable is formulated for corresponding to the time lapse during which buses are held. A following study by Sun and Hickman (2005) investigates the possibility of implementing a stop-skipping policy for operations control in a real-time manner. A non-linear integer programming problem for two different stop-skipping policies is formulated to examine how the performance of the two policies changes with the variability of effective parameters on the route.

Concerning new technologies, Dessouky et al. (2003) examines simulated systems in which holding and dispatching strategies are used. The dependence of system performance on new technologies is also investigated. They combined advanced PT systems with new technologies, such as AVL, APC and wireless communication, to accurately forecast the buses estimated arrival times and to use bus-holding strategies to coordinate transfers.

Strategies to increase efficiency of a high frequency PT route was studied by Daganzo (2009) who shows that without interventions, bus bunching is almost inevitable regardless of the driver's or the passengers' behavior. An adaptive control scheme was analyzed to mitigate the problem. The suggested model, dynamically determines bus holding times at routes control points based on real-time headway information.

Controlling methods using tactics is demonstrated by Hadas and Ceder (2008) in order to alleviate the uncertainty of simultaneous arrivals. They developed a new passenger-transfer concept which extends the commonly used single-point encounter (at a single transit stop) to a road-segment encounter (any point along the road-segment constitutes a possible encounter point). Their works has been extended for PT network

connectivity in Hadas and Ceder (2010b). Furthermore, with the aid of operational tactics, Hadas and Ceder (2010a) improved optimal PT-service reliability via a dynamic programming approach.

In the previous research by Ceder et al. (2013b) the potential of holding at stops and skipping certain individual stops is exhibited in a case study of Auckland, New Zealand. This work continues and refines the research of Ceder et al. (2013b) by introducing the possibility of skip-segment in addition to only skipping an individual stop, and for real-time operational control; the refinement takes place in the optimization formulation. That is, this work refers to three tactic scenarios: no-tactic case, holding and skip individual stops, and holding and skip segments. The objectives of work are to create simulation and optimization frameworks for optimally use the three scenarios and compare between the scenarios using a case study.

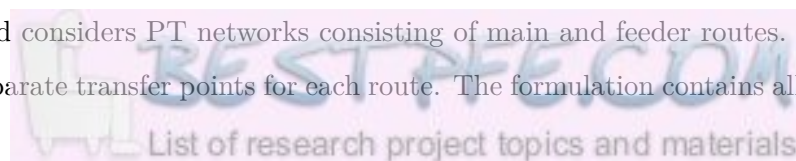
This work is organized as follows. Section 2.3 presents the model formulation and assumptions. Section 2.4 describes the case study in Auckland, New Zealand utilizing simulation, optimization and simulation again. Section 2.5 depicts the analysis and results with a validation procedure. Lastly, Section 2.6 summarizes the findings and draws conclusions.

## 2.3 Formulation and Modeling Framework

This work, as is mentioned above, is an extension of the research by Ceder et al. (2013b) especially in terms of adding the possibility of skipping segments. The methodology of work commences by the use of TransModeler simulation tool, Caliper (2013) to represent a real-life example and to generate random input data for the proposed optimization model. Then standard optimization software, ILOG, IBM (2012), is used to solve optimally a range of different scenarios determined by the simulation runs. Finally, more simulation runs are made, containing the tactics determined by the optimization program, so as to validate the results attained by the model.

### 2.3.1 Model Description

The model developed considers PT networks consisting of main and feeder routes. The transfers occur at separate transfer points for each route. The formulation contains all the



implemented tactics using a deterministic modeling. Analytically the model seeks to attain minimum total passenger travel time and to increase, in this way, the total number of direct transfers. The model formulates the tactics of holding vehicles, skipping individual stops, and skipping segments, as well as indication of missing or making a direct transfer.

The scope of this work is to describe and explain the conjunction of the holding tactic with skip-stop and skip-segment tactics. This model is not addressing individual controlling tactics as appear in the literature, e.g., Sun and Hickman (2005), Delgado et al. (2012, 2013), and Liu et al. (2013), but a combined optimal set of tactics. The control decision consists of when to hold at and skip a stop or to hold at and skip a segment (one or more consecutive stop) given that a direct transferring is feasible. It is to note that the variables and formulation related to the hold and skip stop tactics are similar to those appearing in Ceder et al. (2013b). However, this work is based on new notations and formulation so as to more accurately accommodate the three tactics dealt with, and moreover to allow for an easy extension of the concept used to include more operational tactics.

*State Variables:*

$N$  Set of all bus stops, in which  $n \in N$

$R$  Set of all bus routes in which  $r, r' \in R$

$TF$  Set of all transfer points, in which  $tr \in TF$

$Q_r^{max}$  Passenger capacity of bus of route  $r$

$l_r^n$  Passengers' load of route  $r$  at stop  $n$

$b_r^n$  The number of boarding passengers of route  $r$  at stop  $n$

$a_r^n$  The number of alighting passengers of route  $r$  at stop  $n$

$p_{rr'}^n$  The number of transferring passengers of route  $r$  to route  $r'$  at stop  $n$

$d_r^n$  Bus dwell time of route  $r$  at stop  $n$  (in seconds)  $h_r$  Bus headway of route  $r$

$c_r^n$  Bus running time of route  $r$  at stop  $n$  from the previous stop

$A_r^n$  Bus arrival time of route  $r$  at stop  $n$

$D_r^n$  Bus departure time of route  $r$  at stop  $n$



$\Omega(t)_r^n$  Time penalty function of route  $r$  at stop  $n$

$\Gamma_r^n$  Time to reach a desired stop skipped of route  $r$  at stop  $n$

$T_r$  Bus schedule deviation of route  $r$

$TP_r^{tr}$  Transfer stop of route  $r$  at transfer point of  $tr$

$E_r$  Bus elapsed time of route  $r$  from the previous stop to the current position

$m_r$  Maximum total number of stops of route  $r$

$k_r$  Positional stop of route  $r$  for a snapshot

$\omega$  Ratio between the average speed of a bus and the average walking speed of pedestrian (same ratio for all routes and stops).

*Parameters:*

$\theta_r^n$  The number of passengers of route  $r$  for a bus departing stop  $n$

$\beta_r^n$  The number of passengers waiting at stops further along the routes with respect to route  $r$  and stop  $n$  (future passengers)

$\gamma_r^n$  The number of passengers who wish to have transfers at transfer points with respect to route  $r$  and stop  $n$

$\lambda_r^n$  The waiting time per passenger at previous stops due to applied tactics.

*Decision Variables:*

$HO_r^n$  Bus holding time of route  $r$  at stop  $n$

$S_r^n$  Bus skipping stop of route  $r$  at stop  $n$ ; if stop skipped= 1, otherwise= 0

$Y_{r\acute{r}}^n$  Possible transferring from route  $r$  to route  $\acute{r}$  at transfer stop  $n$ , pre-tactics; if a possible transfer occurs= 0, otherwise= 1

$Z_{r\acute{r}}^n$  Possible transferring from route  $r$  to route  $\acute{r}$  at transfer stop  $n$ , post-tactics; if a possible transfer occurs= 0, otherwise= 1.

*Assumptions:*

The model is designed deterministically. Therefore the following assumptions are made:

- There is foreknowledge of the route information, including average travel times, average passenger demand, average number of transferring passengers and average dwell times.
- Passenger demand is independent of bus arrival time.
- Vehicles are operated in FIFO manner with an evenly scheduled headway.
- Passengers will wait at their stop until a bus arrives (none leaves the system without taking the first arrived bus).
- The bus arriving subsequently to a bus that skipped stop cannot use any of the two tactics considered.
- Passengers onboard a bus that will skip segment will be informed on this action at the time of the decision so as they can alight before or after the skipped segment; it is to note that the formulation of optimization minimizes these type of passengers and in most cases tested it is nil.
- Stops where passengers want to transfer cannot be skipped.
- Planned transfers exist (as part of the operations planning phase).

### 2.3.2 Formulation and Properties of Holding Tactic

Holding a vehicle is a tactic considered operationally for regulating undesired scheduled deviations, reducing bunching and approaching a direct transfer at transfer points. However, using the holding tactic has some drawbacks on the total travel time of the passengers. That is, the holding tactic would affect three groups of passengers: *a)* those onboard the bus defined as  $\theta_r^n$ , *b)* those waiting for the bus further along the route defined as  $\beta_r^n$ , and *c)* those who wish to have transfers defined as  $\gamma_r^n$ . The following formulation can now take place. It is to note that, the term 'route' describes a PT service that serves a series of stops (e.g., Route 858). A route is made up of a collection

of 'trips'; each trip represents a single run, based on a certain departure time, along the series of stops of the route. It is to note that this work refers to routes, not to buses; the buses are only associated with a given route (no interlining). When we're referring to  $a_r^n$ , as the number of alighting passengers of route  $r$  at stop  $n$ , we mean that it can be related to a few buses in a given time period, not to a specific bus.

$$\theta_r^n = l_r^n + b_r^n - a_r^n \quad (2.1)$$

$$\beta_r^n = \sum_{i=n+1}^{m_r} \left[ b_r^i + \sum_{\dot{r} \in R} (1 - Z_{\dot{r}r}^i) p_{\dot{r}r}^i \right] \quad (2.2)$$

$$\gamma_r^n = \sum_{\dot{r} \in R} ((1 - Y_{\dot{r}r}^n) p_{\dot{r}r}^n - p_{r\dot{r}}^n) \quad (2.3)$$

The effect of holding tactic on the change in total passenger travel time with respect to route  $r$  and stop  $n$  is:

$$\Delta TPTT(Holding)_r^n = HO_r^n [\theta_r^n + \beta_r^n + \gamma_r^n] \quad (2.4)$$

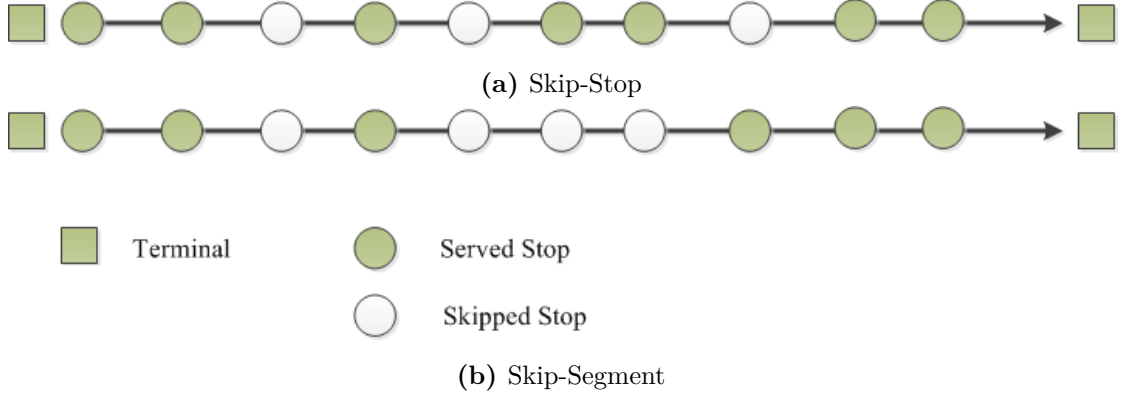
### 2.3.3 Formulation and Properties of Skip-Stop and Skip-Segment Tactics

*Skip-Stop:*

When a major disruption occurs, holding a vehicle, as the only tactic available, cannot guarantee to obviate the headway variation from the schedule. This is true even with holding the following vehicles because these actions may lead to greater schedule deviations (Sun and Hickman, 2005).

Skip-stop is another tactic that can be implemented to decrease the irregularity of service and increase the number of direct transfers. The advantage of skip stop is for passengers who already are onboard the bus and those to board downstream. On the other hand, it has an adverse effect on passengers who want to alight or board at the skipped stop.

*Skip-Segment:*



**Figure 2.1:** Skip-Stop and Skip-Segment tactics

The skip of individual stop tactic has the limit that no more than one stop can be skipped in a row. However if, for instance, some stops are close to each other and only a very few passengers will be impacted from skipping those stops, another tactic can take place as is illustrated by Figure 2.1. That is, to consider skip-segment tactic, where a segment is defined as a group of one or more stops. One of the assumptions of this work is that passengers onboard a bus that will skip segment will be informed immediately on this action at the time of the decision so that they can alight before or after the skipped segment. This assumption is considered in the optimization formulation and in most of the cases simulated the amount of this type of passengers was approaching zero; it is because of minimizing the total travel time. In other words, if the amount of passengers of this type is large, this tactic of skip segment won't take place. The formulation of this type of passengers is explicated as follows.

Let consider the end and start-again service stops of the skipped segment. That is, the end stop is the last stop served before the skipped segment, and the start-again stop is the first stop served after the skipped stop. Passengers who want to alight in the skipped segment and alight at the end-service stop will have extra time to reach their destination (within the skipped segment) to be termed "*forward time*",  $\Gamma_{(forward)}$ . However to determine the actual additional travel time, the bus running time to the desired skipped stop has to be subtracted, and thus the following formulation is used.

$$\Gamma_{r(forward)}^n = (\omega - 1) \sum_{i=1}^n c_r^i \left( \prod_{i=q}^n S_r^i \right) \quad \forall (n, q \in N) \{1 \leq q < n\} \quad (2.5)$$

At the same time passengers alighting at the start-again service stop will need to go back

to their destination stop, and their time is termed "*backward time*",  $\Gamma(\text{backward})$ . In this case additional bus running is added, and the passengers to use this way, to reach their destination, will save the dwell times of the skipped stops. These considerations yield:

$$\Gamma_{r(\text{backward})}^n = (\omega + 1) \sum_{i=n+1}^{m_r} c_r^i \left( \prod_{i=n}^q S_r^i \right) - \sum_{i=1}^n S_r^i d_r^i \quad \forall (n, q \in N) \{1 \leq n < q\} \quad (2.6)$$

It is possible that these passengers will decide to walk, thus a "*walking time*" penalty function is described as:

$$\Omega(t)_{r(\text{walking})}^n = \min \left( \Gamma_{r(\text{forward})}^n, \Gamma_{r(\text{backward})}^n \right) \quad (2.7)$$

The alternative of walking is the waiting for the next bus to bring these passengers to their destination. The waiting time associated with upstream stops is designated  $\lambda_r^n$  to be:

$$\lambda_r^n = \sum_{i=k_r}^{n-1} \left( S_r^i d_r^i - HO_r^i \right) \quad (2.8)$$

The "*waiting time*" penalty function is then determined by the following equation with consideration of schedule deviation  $T_r$ :

$$\Omega(t)_{r(\text{waiting})}^n = (h_r - T_r + \lambda_r^n) \quad (2.9)$$

Two penalty functions were established: walking time and waiting time penalties, with now a new definition of "*total time*" penalty being the minimum of the two as follows.

$$\Omega(t)_{r(\text{total})}^n = \min \left\{ \Omega(t)_{r(\text{walking})}^n, \Omega(t)_{r(\text{waiting})}^n \right\} \quad (2.10)$$

Consequently the effect of the skip-segment tactic on the change of the total travel time for route  $r$  and stop  $n$  is:

$$\begin{aligned} \Delta TPTT(\text{Skip} - \text{Segment})_r^n = \\ S_r^n \left[ a_r^n \Omega(t)_{r(\text{total})}^n + b_r^n (h_r - T_r + \lambda_r^n) - d_r^n (l_r^n + \beta_r^n) \right] \end{aligned} \quad (2.11)$$

### 2.3.4 Formulation and Properties of Transfers

Synchronized transfers mean that two or more buses, or other *PT* vehicles, meet at the same time at a transfer point. As told, this can be improved by the use of real-time operational tactics. For missed transfers passengers have to tolerate a waiting time of  $(h_r - T_r)$  where  $h_r$  is the headway at route  $r$ . Therefore a direct transfer occurs if the following holds.

$$Y_{r\acute{r}}^n + Y_{\acute{r}r}^n = 0 \quad (2.12)$$

$$Z_{r\acute{r}}^n + Z_{\acute{r}r}^n = 0 \quad (2.13)$$

In this model a possible transfer  $Y_{r\acute{r}}^n$  (before implementing tactics) occur if bus departure time on route of  $\acute{r}$  is after the bus arrival time on route  $r$  and vice versa for  $Y_{\acute{r}r}^n$ . Same arguments apply for  $Z_{r\acute{r}}^n$  and  $Z_{\acute{r}r}^n$  after utilizing tactics. If the following conditions hold direct transfers will be possible and none of the buses will be late at a transfer point.

$$A_r^n = \sum_{i=k_r}^n c_r^i - E_r \quad (2.14)$$

$$D_{\acute{r}}^n = \sum_{i=k_{\acute{r}}}^n c_{\acute{r}}^i - E_{\acute{r}} + d_{\acute{r}}^n \quad (2.15)$$

$$\text{if } D_{\acute{r}}^n \leq A_r^n, \text{ then } Y_{r\acute{r}}^n = 1 \quad \forall (p_{r\acute{r}}^n + p_{\acute{r}r}^n \geq 1) \quad (2.16)$$

Subsequently the effect of transfers on the change of the total travel time for route  $r$  and stop  $n$  is:

$$\Delta TPTT(Transfer)_r^n = \sum_{\acute{r} \in R} [p_{r\acute{r}}^n (Z_{r\acute{r}}^n (h_{\acute{r}} - T_r + \lambda_r^n) - Y_{r\acute{r}}^n (h_{\acute{r}} - T_r))] \quad (2.17)$$

### 2.3.5 Objective Function

According to the formulations derived of the total passenger travel time, an objective function for the proposed model can be written as:

$$\min \sum_{r \in R} \sum_{n \in N} \Delta TPTT \{ (Holding)_r^n + (Skip - Segment)_r^n + (Transfer)_r^n \} \quad (2.18)$$

This objective function, of minimum total travel time, is subject to the following constraints.

### 2.3.6 Constraints

Transfer points cannot be skipped is stated as:

$$S_r^n \left[ \sum_{r' \in R} (p_{rr'}^n + p_{r'r}^n) \right] = 0 \quad (2.19)$$

Direct transferring would occur only if the following exists:

$$A_r^n - \lambda_r^n - D_r^n - HO_r^n + \lambda_r^n \leq M * Z_{rr}^n \quad \forall (p_{rr}^n + p_{rr}^n \geq 1),$$

$M$  is a large number (2.20)

Tactics can't be applied on stops that a bus is not going to or are already passed:

$$HO_r^n = 0 \quad \text{when } (n < k_r) \quad (2.21)$$

$$S_r^n = 0 \quad \text{when } (n < k_r) \quad (2.22)$$

It is not allowed to skip the first stop:

$$S_r^1 = 0 \quad (2.23)$$

Moreover no skipping and holding at the same stop are allowed:

$$\{S_r^n * HO_r^n = 0\} \quad (2.24)$$

This constraint can be simplified and reformulated. Let  $M$  denotes a large number; thus constraint (2.23) is exchanged with the following constraints:

$$\text{if } S_r^n = 1, \text{ then } HO_r^n \leq M * (1 - S_r^n) \quad (2.25)$$

$$\text{if } HO_r^n > 0, \text{ then } M * S_r^n \leq HO_r^n \quad (2.26)$$

The maximum holding time is not more than half the headway of the route:

$$HO_r^n \leq 1/2h_r \quad (2.27)$$

If a transfer occurs at pre-tactics situation the same apply to with-tactics situation:

$$Z_{r\dot{r}}^n \leq Y_{r\dot{r}}^n \quad (2.28)$$

If direct transferring is possible without the use of any tactic, there is no need to interfere; this constraint is expressed as follows where  $M$  as a large number:

$$\sum_{i=TP_r^{tr-1}}^{TP_r^{tr}} S_r^i \leq \sum_{tr \in TF} M * Y_{r\dot{r}}^{tr} \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r \right) \quad (2.29)$$

$$\sum_{i=k_r}^{TP_r^{tr}} S_r^i \leq \sum_{tr \in TF} M * Y_{r\dot{r}}^{tr} \quad \forall \left( TP_r^{tr} > k_r > TP_r^{tr-1} \right) \quad (2.30)$$

$$\sum_{i=k_r}^{TP_r^1} S_r^i \leq M * Y_{r\dot{r}}^1 \quad \forall \left( TP_r^1 > k_r \right) \quad (2.31)$$



If the use of tactics does not result in a transfer, no tactics are applied:

$$\sum_{i=TP_r^{tr-1}}^{TP_r^{tr}} S_r^i * \prod_{tr \in TF} Z_{r\dot{r}}^{tr} < 1 \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r \right) \quad (2.32)$$

$$\sum_{i=K_r}^{TP_r^{tr}} S_r^i * \prod_{tr \in TF} Z_{r\dot{r}}^{tr} < 1 \quad \forall \left( TP_r^{tr} > k_r > TP_r^{tr-1} \right) \quad (2.33)$$

$$\sum_{i=K_r}^{TP_r^1} S_r^i * Z_{r\dot{r}}^1 < 1 \quad \forall \left( TP_r^1 > k_r \right) \quad (2.34)$$

Constraints (2.32-2.34) can be simplified. Let denote  $Im$  as:

$$Im = \sum_{tr \in TF} Z_{r\dot{r}}^{tr} \quad (2.35)$$

The maximum value of  $Im$  implies that the use of tactic does not result in a transfer and  $Z = 1$  for all routes at all transfer points. Thus the following constraint ensures the use of tactics when a transfer occurs.

$$if \ Im = size \ of \ Z_{r\dot{r}}^{tr}, \ then \ \sum_{i=TP_r^{tr-1}}^{TP_r^{tr}} S_r^i = 0 \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r \right) \quad (2.36)$$

The same applies for Constraints (2.33) and (2.34).

For using Skip-stop (not segment) tactic the following constraint is for skipping only one stop in a row:

$$S_r^n + S_r^{n+1} \leq 1 \quad (2.37)$$

To restrict the number of passengers onboard when the bus departs the stop, the following checking constraint (true or false) is introduced:

$$\theta_r^n \leq Q_r^{max} \quad (2.38)$$


### 2.3.7 Model Optimization

In the previous section the problem was formulated as a mixed-integer programming (MIP). The formulation of the problem with the three scenarios (no-tactics, holding&skip-stop, holding&skip-segment) can be solved using constrained programming (CP) technique. The CP is an efficient approach to solving and optimizing problems that are too irregular for mathematical optimization. The reasons for these irregularities (IBM, 2012) are: (i) the constraints are nonlinear in nature, (ii) a non-convex solution space exists with many local-optimal solutions and (iii) multiple disjunctions exist resulting in poor returned information by a linear relaxation of the problem. A CP engine makes decisions on variables and values and, after each decision, performs a set of logical inferences to reduce the available options for the remaining variables' domains. This is in comparison with a mathematical programming engine that uses a combination of relaxations (strengthened by cutting-planes) and 'branch and bound'. CP solver is an appropriate tool for discrete optimization problem (Hooker, 2006). Optimization programming language (OPL) using ILOG (IBM, 2012) allows us to execute the optimization problem with the benefits of both MIP and CP to reduce the computation time.

## 2.4 Case Study of Real-Time Tactics Implementation

Examination of the model developed took place with a real-life case study. The data of the case study was collected in Auckland, New Zealand. It is to note that all buses of the Auckland transport network are equipped with AVL systems. The primary benefits of the AVL system are in the communication and processing of data for service monitoring, fleet management, and traveler information as is describe by Hickman (2004). AVL can display the current location of the bus, whether or not it is on schedule, and any other important messages that may be communicated between the driver and the control center. In this work with the consideration of AVL systems, it becomes possible to provide passengers with information on how the service is going to be delivered, e.g., passengers onboard a bus that will skip segment will be informed on this action at the time of the decision so as they can alight before or after the skipped segment. In addition, AVL data are used to analyze bus travel times and schedule adherence (to implement holding

tactics). This means that real-time information on bus locations can be used to predict bus arrivals at the transfer points and to determine bus schedule deviations.

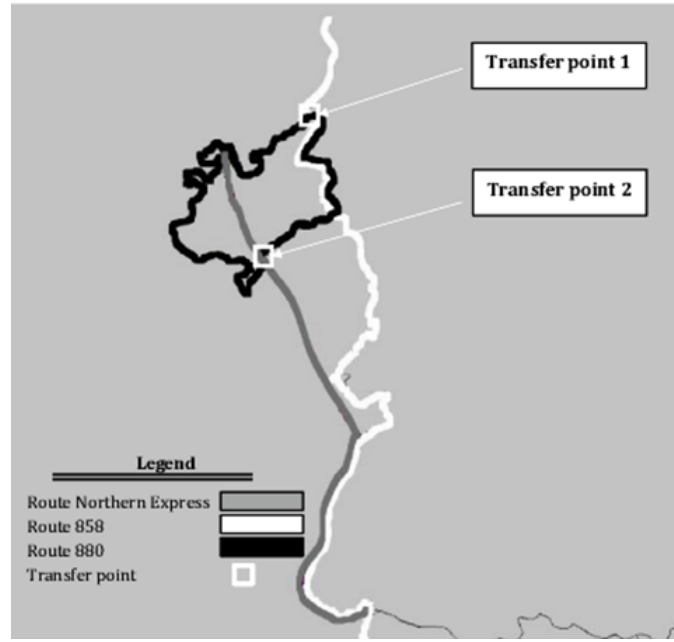
The PT network consists of three bus routes and two transfer points. The first route is known as Northern Express with a dedicated lane that runs from the suburb across the Auckland CBD area and has quite a high number of passengers during Peak hours. The second route, Route 858, runs north-south (east of the first route), and the third route, Route 880, is a loop that serves as a feeder route. Figure 2.2 illustrates the three routes and the two transfer points used.

### 2.4.1 Data

The data was recoded on the buses running on the routes shown in Figure 2.2. The available data are route characteristics-based; that is, stop ID, longitude, latitude, stop sequence, stop flag, stop code, stop name, route ID, user ID, point ID, and route number. Bus capacity of 60 passengers is assumed with 40 seated passengers and 20 standing (Transit Capacity, 1999).

The simulation package used, TransModeler 3.0 (Caliper, 2013), considers passenger crowding for the calculation of the dwell time. That is, it takes longer to board or alight a bus if there are more standing passengers. In addition, bus dwell times were taken from Dueker et al. (2004) for simulation use. It affects whether or not the stop be skipped. The dead time (time spent at the stop without boarding or alighting) is set to 4 seconds as the default value of TransModeler. The study by Dueker et al. (2004) showed that the boarding time per passenger was found to be 3.48 seconds and alighting time per passenger 1.70 seconds.

Passenger demand in terms of OD matrix is being estimated based on the average number of passengers boarding and alighting at each stop, from the first stop of the route to a transfer point. That is, OD is estimated based on proportions of the number of boarding, alighting and onboard passengers; the time and location of boarding and alighting of passengers are provided. That is, the average proportion of boarding and alighting passengers at all stops before a transfer point is applied to the transfer point and the difference is the number of transferred passengers. Average headways and dispatch times are assumed to be known at both Transfer Point 1 and Transfer Point 2.



**Figure 2.2:** Bus system and the study routes, Auckland, New Zealand.

In addition, vehicle seating capacity considered is 40 and vehicle headways considered are 5, 10, 15 and 20 min (same for all routes).

#### 2.4.2 Network Simulation

The case study was simulated for analysing and validating the performance of the model before and after implementation of the tactics. Moreover, the PT network has been simulated for handling the concept of synchronized transfers.

The simulation software TransModeler, (Caliper, 2013) has been used to simulate the network. At the same time the model was coded into the optimization package ILOG by (IBM, 2012).

## 2.5 Result and Analysis

Three scenarios are used for the simulated network. For the first scenario 'No-Tactics' direct transfers occurred infrequently. The other two scenarios are 'holding & skip-stop' and 'holding & skip-segment'. All scenarios are examined for different headways: 5min, and 10min to represent short headways and 15min and 20min as long headways.

### 2.5.1 Simulation of the Case Study

The simulation was executed for a time period of 24h in order to accumulate enough statistical data required for the three scenarios. The first run, naturally, represents the current situation and no tactics. The evaluation of this step includes the number of direct transfers and deviation from the bus schedule at different locations. In addition, reference stops have been selected to determine the deviation from scheduled arrivals at the transfer points. Thus when a bus is arriving at a reference stop, four stops before the transfer point, the other bus could be at a different location than supposed to be according to the timetable. By dividing the other bus's route into small segments, the probability of it being present at the location expected can be found. This enables the investigation of bus schedule deviation at the stops located before and at the transfer point. Consequently the suggested tactics can then be applied for compensating the schedule deviations. The simulation results show that schedule deviations are between  $-247$  and  $+177$  seconds. These results enable to estimate the location of the buses. Thirteen different bus schedule deviations have been introduced to determine the probability of the bus location. The probability is obtained by running the simulation a few times.

#### 2.5.1.1 Simulation Output

The information generated at the end of the simulation run is route name, physical stop number, trip number, scheduled headway, arrival time, departure time, stop name, headway from previous vehicle, vehicle number, trip time, number of alighting and boarding passengers, and vehicle dwell time. These outputs are exported for sorting and filtering for separating out specific data required (e.g., for a particular bus or transfer point). The first hour of simulation is always discarded to eliminate the impact of initial conditions and to allow for the model time to stabilize (warm-up period). Then the data is plugged into the ILOG optimization model in order to get the optimum solution (tactics) for different scenarios.

#### 2.5.1.2 Optimization Process

The information of the buses in each of the prescribed cases was input into the optimization model. Then the optimal scenario tactic-related is determined for each schedule-deviation

case so as to minimize the total passenger travel time; this optimal solution will naturally tends to maximize the number of direct transfers. For instance, at Transfer-point 1, eleven cases have been investigated, and for each case the optimal tactic is suggested. The results appear in Table 2.1(a) and (b).

Table 1 shows the optimal tactics for each scenario and the potential saving of total passenger travel time. In Table 2.1(a) a group of stops has been skipped for different cases of schedule deviations. For example, in the first row at 128 sec delay of Route 858, skipping consecutive stops will start at Stop 101 and will end at Stop 107; the holding time is 61 seconds and the direct transfer does occur from Route 858 to Route 880 with a total travel time saving of 6592 seconds. The 'holding & skip-segment' combined tactics results in a more saving of passenger travel time compared with the 'holding & skip-stop' combined tactic. For a deviation between 0 and 27 seconds, direct transfer occurs without the implementation of any tactic. The use of the 'holding & skip-segment' enabling direct transfers around 100 seconds schedule deviation whereas by using the 'holding & skip-stop' combined tactics for this case it results in a missed transfer; the third row from bottom of Table 2.1(a) and (b) emphasizes it. Table 2.1 exhibits that for deviations over 100 seconds, none of those scenarios of tactics is effective and passengers will miss a direct transfer.

### 2.5.2 Validation Using Simulation

The methodology developed utilizes simulation (with the case study input), optimization and simulation runs with the outcome of the deterministic optimization for validation under a stochastic framework. When the optimization program recommends tactics to deploy in the simulation, it is possible to evaluate the estimated percent/proportion of direct transfers with tactics (based on the optimization model projection); in addition also to find out how often the direct transfer is actually attained under stochastic conditions. This approach is used and entitled 'optimization&simulation-based' as opposed to the results of the optimization only entitled 'optimization-based'.

### 2.5.3 Results and Performance of the Proposed Model

Table 2 and Figure 3 summarize the main results of the simulated case study. It is to note that a careful check of the ILOG-based formulation of the holding and skip-stop tactic of

**Table 2.1:** Results of Optimization at Transfer-point1

(a) Optimal 'Holding & Skip-Segment' scenario

Bus Location	Routs858		Routs880		Transfers		Modification
Time Deviation from Schedule (sec)	Skipped Segment	Holding at Transfer 1	Skipped Segment	Holding at Transfer-point 1	Improved Direct Transfers; from route → to route (Z)	DT	$\Delta TPTT$
-128	101...107			61 sec	858→880	YES	-6591.907
-92	102...107			35 sec	858→880	YES	-6457.055
-69	103...107			19 sec	858→880	YES	-5857.552
-47	103...107				858→880	YES	-6473.152
-23	104...107				858→880	YES	-5276.088
0					-	YES	0
27					-	YES	0
60			89...92		880→858	YES	-3425.776
100		18 sec	89...92		880→858	YES	-1748.266
140					-	NO	0
177					-	NO	0

(b) Optimal 'Holding & Skip-Stop' scenario

Bus Location	Routs858		Routs880		Transfers		Modification
Time Deviation from Schedule (sec)	Skipped Stop	Holding at Transfer-point 1	Skipped Stop	Holding at Transfer-point 1	Improved Direct Transfers; from route → to route (Z)	DT	$\Delta TPTT$
-128	101, 103, 105, 107			96 sec	858→880	YES	-2700.087
-92	102, 104, 106			68 sec	858→880	YES	-2780.124
-69	103, 105, 107			41 sec	858→880	YES	-3404.499
-47	103, 105, 107			18 sec	858→880	YES	-4149.699
-23	104, 106			6 sec	858→880	YES	-3577.471
0					-	YES	0
27					-	YES	0
60		3 sec	90,92		880→858	YES	-2804.691
100					-	NO	0
140					-	NO	0
177					-	NO	0

Note: DT = YES/NO for direct transfer occurrence

Ceder et al. (2013b) revealed some inaccuracies, thus it was modified in this work. The optimization process time, using Intel Core<sup>TM</sup> i5-2500 CPU 3.30 GHZ and 8.00 GB RAM, depends on the positional stop. The resulting process time varies between 5-13 seconds which is reasonable for a real-time consideration. Table 2.2 (a) and (b) describes the probability (proportion) of direct transfers for each scenario using four types of headways (same for all routes): 5, 10, 15 and 20 minutes. The three scenarios are designated 'No-Tactics', H-S (holding and skip-stop), and H-SS (holding and skip-segment). The last column of Table 2.2 depicts the percentage of improvement of each combined tactic over the No-Tactics scenario in terms of the number of direct transfers.

As expected the validated results in Table 2.2 under 'optimization&simulation-based' reduce the probability of direct transfers, but not significantly. The impressive part is the % improvement of the number of direct transfers with tactics compared with the

**Table 2.2:** Direct Transfers for each scenario

(a) Direct Transfers at Transfer-point 1				
Headway (same for all routs)	Scenario	Probability of Direct Transfers		Improvement (%)
		Optimization based	Optimization & simulation based	
5min	No Tactics	0.28	N/A	N/A
	H-S	0.59	0.55	99.82%
	H-SS	0.71	0.69	148.62%
10min	No Tactics	0.30	N/A	N/A
	H-S	0.62	0.58	91.95%
	H-SS	0.71	0.69	129.21%
15min	No Tactics	0.32	N/A	N/A
	H-S	0.86	0.83	156.18%
	H-SS	0.90	0.89	176.50%
20min	No Tactics	0.31	N/A	N/A
	H-S	0.95	0.93	203.85%
	H-SS	0.95	0.94	206.86%

(b) Direct Transfers at Transfer-point 2				
Headway (same for all routs)	Scenario	Probability of Direct Transfers		Improvement (%)
		Optimization based	Optimization & simulation based	
5min	No Tactics	0.10	N/A	N/A
	H-S	0.12	0.12	15.87%
	H-SS	0.18	0.18	70.38%
10min	No Tactics	0.11	N/A	N/A
	H-S	0.20	0.20	74.77%
	H-SS	0.29	0.28	154.21%
15min	No Tactics	0.17	N/A	N/A
	H-S	0.56	0.56	224.82%
	H-SS	0.56	0.56	224.82%
20min	No Tactics	0.19	N/A	N/A
	H-S	0.65	0.64	232.95%
	H-SS	0.65	0.64	232.95%

Note: H-S = holding and skip-stop; H-SS = holding and skip-segment; N/A = data not available

No-Tactics scenario, which naturally increases with the headway of service.

The number of direct transfers at Transfer-point 2 is generally lower for short headways than the numbers attained for Transfer-point 1. This is because Transfer-point 2 is the second stop of the Northern express route and thus the variability of its travel and arrival times, for short headways (5 and 10 minutes), is relatively small. This is not the case for longer headways.

Table 2.2 results demonstrate the significant better results for the holding and skip-segment combined tactic than for the holding and skip-stop combined tactic especially for short headway cases. This can be also observed in Figure 3 which illustrates the



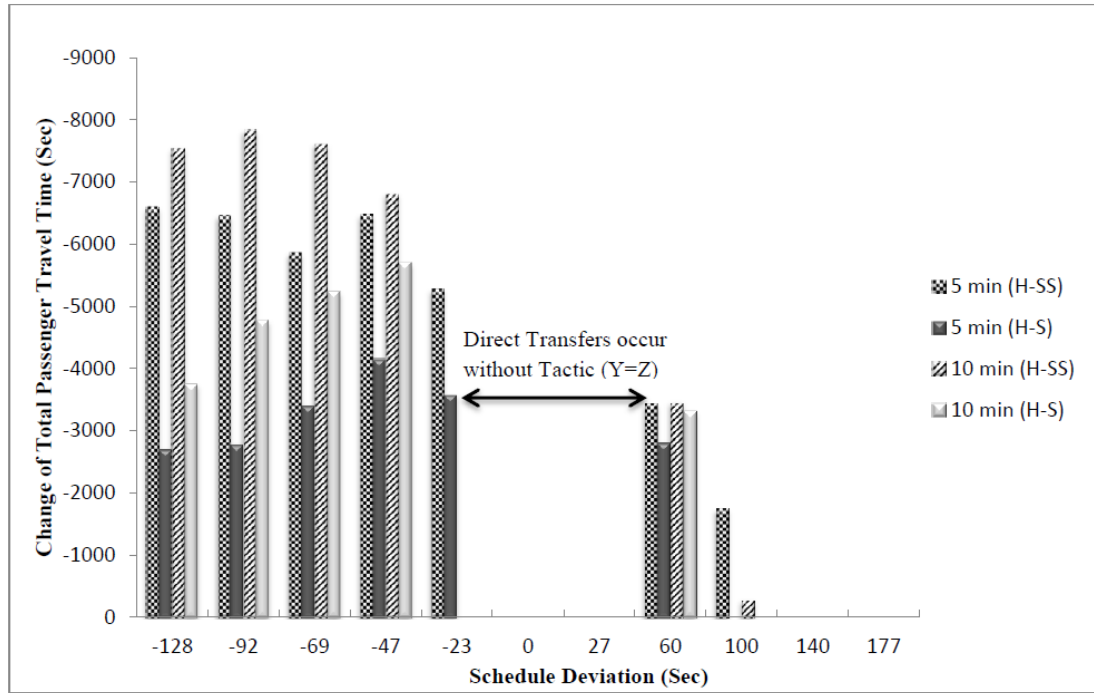
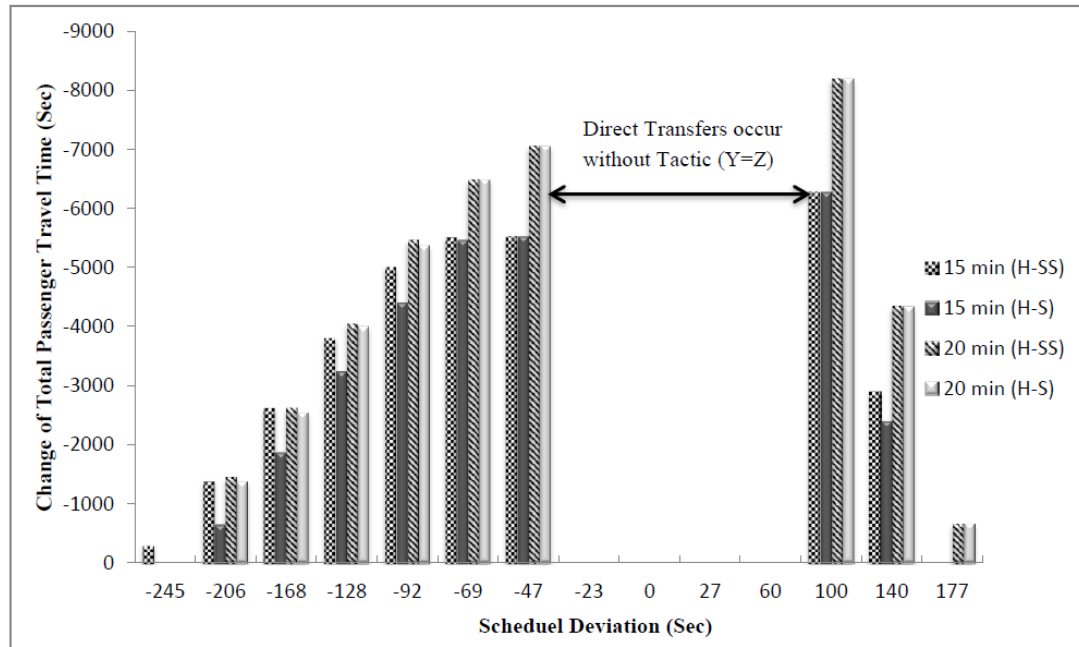
effect of the model on the total passenger travel time for Transfer-point 1.

In Figure 2.3 the results of short headways, in Part (a), are completely different from the results of the long headways, in Part (b) in terms of the shape of the trend before and after the No-Tactics zone. Figure 2.3 shows that by using the combined tactics, compared with the No-Tactics scenario, a considerable reduction of total travel time is attained. Parts (a) and (b) of Figure 2.3 show that when the schedule deviation tends to zero, the maximum saving of total travel time occurs without the use of any tactics; this max travel time saving coincides with max numbers of direct transfers. It is also observed, from Figure 2.3, that the schedule-deviation interval, in which no tactic is used, is larger for long than short headways.

The different shapes of trend in Parts (a) and (b) of Figure 2.3 deserve explication. Figure 2.3(a) illustrates that a larger reduction of total passenger travel time is possible when the bus is behind schedule. This suggests that passengers waiting for a late bus prefer, in the short headway cases, to continue to wait than to find an alternative solution (walking or use of another travel mode). In this case it worth applying the combined tactics. Figure 2.3(b) demonstrates an entirely different pattern; it shows that, in the long headway case, travel time is not saved much for large schedule deviations. That is, unreliable service for long headway cases cannot be compensated by the use of tactics and passengers will tend to find, for such a service, alternative solutions. However, if the deviations are reasonable, the use of tactics can save travel time and increase the number of direct transfers. It is to note that the deviations (in seconds) of Figure 2.3 are based on a few assumptions, thus cannot be translated to exact figures of being behind or ahead of the planned schedule. Instead their trends provide a new insight of when to use the combined tactics proposed.

### 2.5.3.1 Headway Distribution

In addition to the validation of the optimization results for the different scenarios, it is also possible to monitor the headway variation for a typical simulation run. Bus bunching takes place when headways between buses are irregular. Identifying and understanding the distribution and attributes of bus bunching helps to ensure appropriate control strategies. The simulation results illustrate the headway frequency distribution, over hours of day and stops along a route. Figure 2.4 shows an example of headway

(a)  $\Delta TPTT$  for Short Headway (5 min, 10 min)(b)  $\Delta TPTT$  for Long Headway (15 min, 20 min)

**Figure 2.3:**  $\Delta TPTT$  with the two combined tactics of holding and skip-stop/segment at Transfer-point 1

distribution before and after applying the tactics for a time period of 24h in order to accumulate enough data. Route 858 is selected because this route is the longest route of the case study and is long enough for bus bunching to appear with 5 min headway. Based on Molnar (2008), bunching is considered where the headway between buses is less than or equal to two minutes.

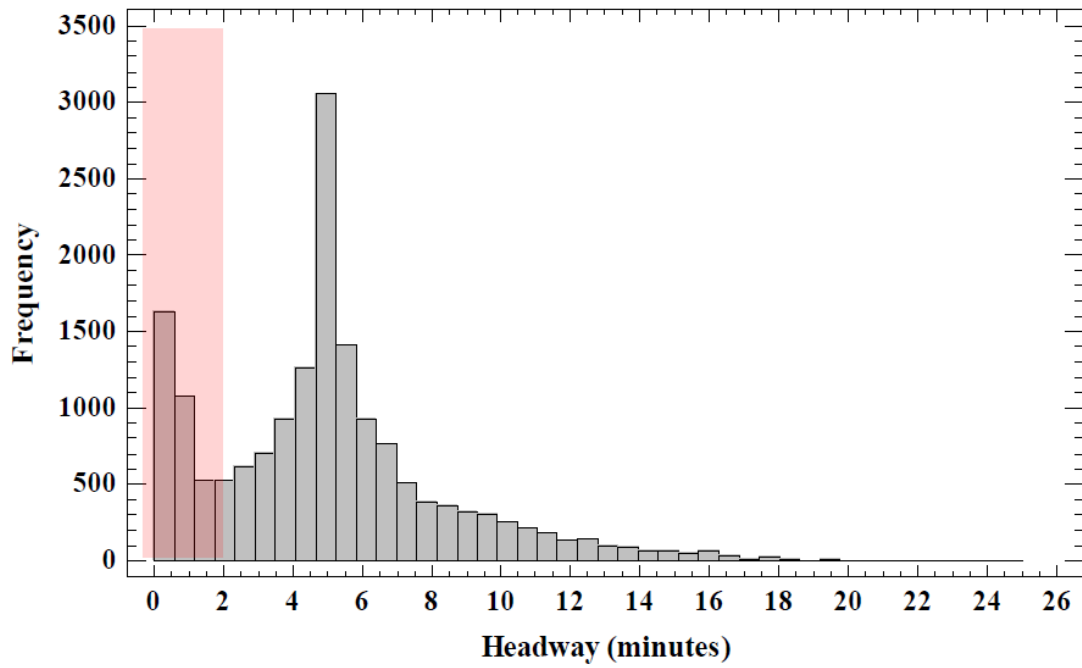
Accordingly, Figure 2.4(a) shows that 20.6% of the buses are bunched up when there is no control on the PT services compared with about 13% when utilizing tactics as it appeared in Figure 2.4(b). That is, the performance of 7.6% buses has been significantly improved. It is to note that applying tactics avoid bunching before the transfer points; this undoubtedly assists in making direct transfers.

### 2.5.3.2 Sensitivity Analysis

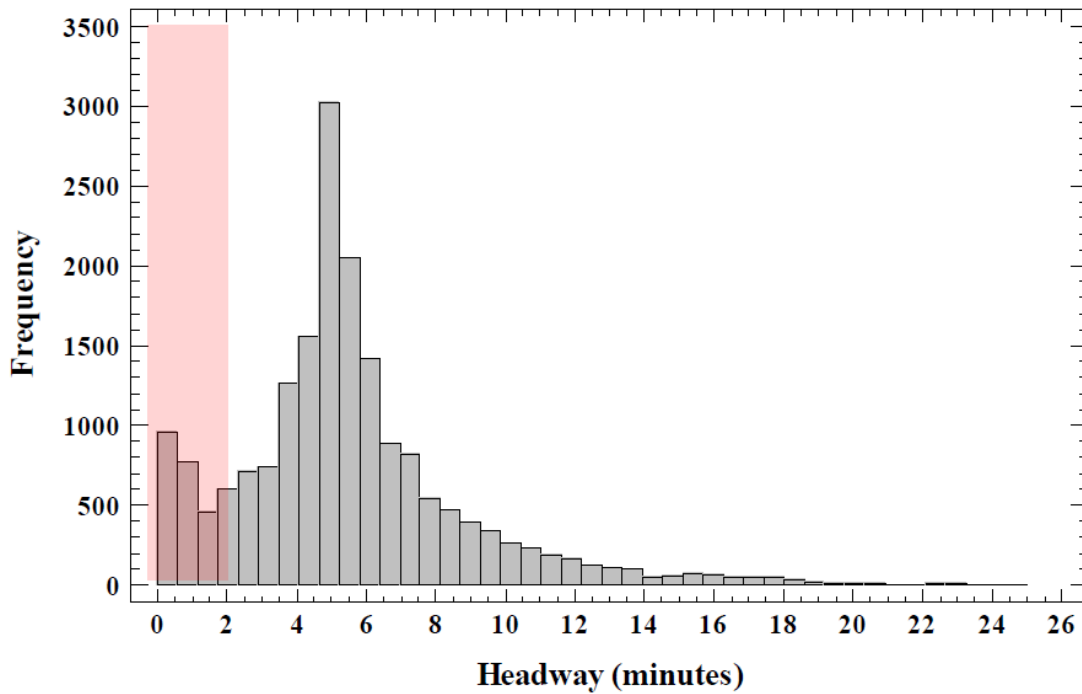
Sensitivity analysis of the results was performed on the objective-function components using the Tornado-diagram method in Figure 2.5. The purpose of a tornado diagram is to graphically show the impact of variations of the variables on model output, and ranking it in order of importance (Eschenbach, 1992).

Each black bar in Figure 2.5 illustrates the changes to the total passenger travel time when the variable is ranged between its lower- and upper-bound values. Certainly, a longer bar reflects greater sensitivity. The variables considered are short and long headways, in Figure 2.5a, and Figure 2.5b, respectively. In each figure there is a solid vertical line representing the base, or most frequent, case of direct transfer. For instance, the first and most sensitive bar of Figure 2.5a is related to changes of total passenger travel time (TPTT) when using the skip-stop tactic. If this tactic is not used, TPTT is not changed, and  $\Delta TPTT = 0$  and this is the upper bound of TPTT for the skip-stop tactic. However, if using the skip-stop tactic with its maximum possibilities then TPTT will be reduced and  $\Delta TPTT = -6768.307$ , or in the other words, this the lower bound of the  $\Delta TPTT$ . It is to note, as expected, that making transfer for a long headway is an important factor requiring more attention.



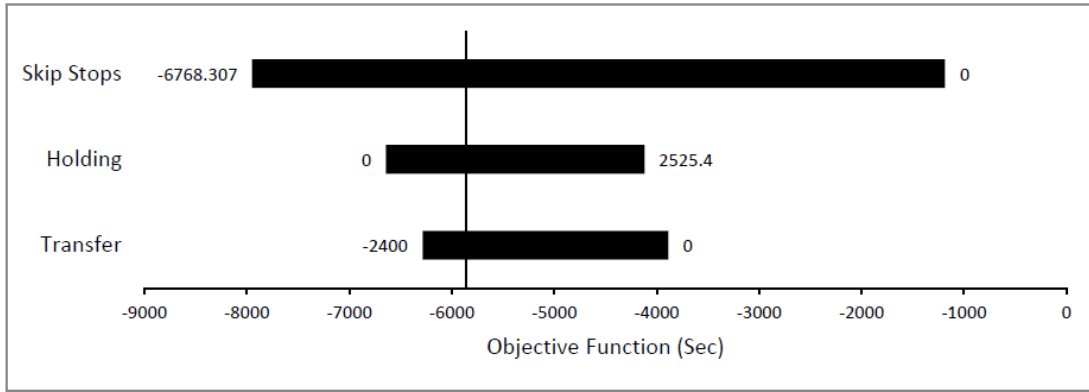


(a) Headway distribution before tactics

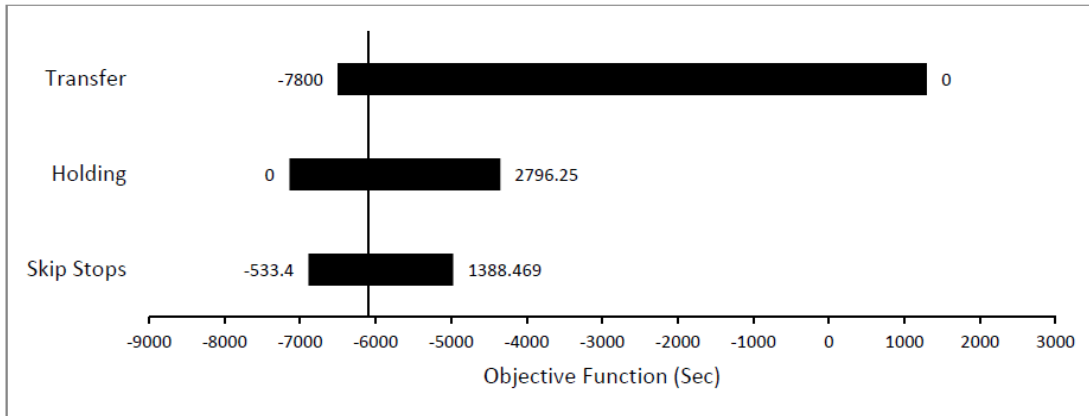


(b) Headway distribution after tactics

**Figure 2.4:** Headway distribution of Route 858



(a) Sensitivity of the objective-function components for variations of short headways



(b) Sensitivity of the objective-function components for variations of long headways

**Figure 2.5:** Sensitivity of total passenger travel time to variations of short and small headways for each component (skip-stop/segment, holding, and transfer)

## 2.6 Concluding Remarks

Handling efficiently and effectively real-time vehicle control is of major concern of public transport (PT) operators. This work focuses on reducing the uncertainty of missed transfers by the use of control tactics in real-time operation. The work is both a continuation and refinement of a recent study by Ceder et al. (2013b) especially in terms of adding the possibility of skipping segments, where each segment is a group of one or more stops. The methodology developed commences by the use of a simulation tool to represent a real-life example, in Auckland, New Zealand in this work, and to generate random input data for the proposed optimization model. Then standard optimization software is used to solve optimally a range of different scenarios determined by the simulation runs. Finally, more simulation runs are made, containing the tactics determined by the optimization program, so as to validate the results attained by the model.

The skip of individual stop tactic has the limit that no more than one stop can be skipped in a row. However if, for instance, some stops are close to each other and only a very few passengers will be impacted from skipping those stops, the skip-segment tactic can take place. This work examined three scenarios: No-Tactics, holding and skip-stop, and holding and skip-segment; the two latter scenarios are combined operational tactics.

The analysis shows significant better results for the holding and skip-segment combined tactic than for the holding and skip-stop combined tactic especially for short headway cases. In addition, the results exhibit that: (i) by using the combined tactics, compared with the No-Tactics scenario, a considerable reduction of total travel time is attained, (ii) when the schedule deviation tends to zero, the maximum saving of total travel time occurs without the use of any tactics; this max travel time saving coincides with max numbers of direct transfers, and (iii) passengers waiting for a late bus prefer, in the short headway cases, and for a not so late and not so ahead-of-time bus, in the long headway cases, to continue to wait than to find an alternative solution (walking or use of another travel mode); a behaviour that makes it worth applying the combined tactics. The limitation of this study is mainly related to the assumptions used for constructing the model. For instance, for a highly varied time-independent passenger demand the model may need to be further adjusted to account for large errors.

Future research may continue to develop a library of operational tactics especially for the nowadays advance of communication technologies. These tactics can reduce, among other things, the uncertainty of simultaneous arrivals of two or more vehicles at a transfer point, and in this way to reduce or diminish the missed transfer case which is one of the undesirable features of the PT service.

The next chapter continues, rectifies the limitations and advances the research of **Chapter 2** by introducing a new operational tactic "*short-turn*" and new simulation framework (agent-based simulation).



## Chapter 3

# A Robust, Tactic-Based, Real-Time Framework for Public-Transport Transfer Synchronization

*Published in:*

*Transportation Research Part C: Emerging Technologies.* **60**, 105-123.

(Nesheli and Ceder, 2015b)

### 3.1 Abstract

Missed transfers affect public transport (PT) operations by increasing passenger's waiting and travel times and frustration. Because of the stochastic and uncertain nature of PT systems, synchronized transfers do not always materialize. This work proposes a new mathematical programming model to minimize total passenger travel time and maximize direct (without waiting) transfers. The model consists of four policies built on a combination of three tactics: holding, skip-stops, and short-turn, the last applied, for the first time, as a real-time control action. The concept is implemented in two steps: optimization and simulation. An agent-based simulation framework is used to represent real-life scenarios, generate random input data, and validate the optimization results.



In order to assess the robustness of this framework, a wide range of schedule-deviation scenarios are defined using efficient algorithms for solving the control models within a rolling horizon structure. A case study of the Auckland, New Zealand, PT system is described for assessing the methodology developed. The results show a 4.7% reduction in total passenger travel time and a more than 150% increase in direct transfers. The best impressive results are attained under short headway operations.

## 3.2 Introduction

A common strategy implemented internationally by public transport (PT) agencies is to develop an integrated, multi-modal transport system in order to provide travelers with a viable alternative to private cars. An important element for retaining existing users and attracting new passengers is to improve serviceability by offering routes with "seamless" transfers. Ceder (2007, 2015) defined a well-connected transit path as an advanced, attractive transit system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, part of the door-to-door passenger chain.

The facilitation of inter-route, inter-modal, or intra-modal transfers is a key component in achieving full integration of the network. The use of PT transfers has the advantages of reducing operational costs and introducing more flexible and efficient route planning. However, the main drawback, from the passengers' perspective, is the inconvenience of traveling multi-legged trips; more than a few research studies have shown evidence that PT users are negatively inclined to make transfers if it involves uncertain waiting time (Ceder et al., 2013a). To diminish the waiting time caused by transfers, Ceder and Tal (2001) introduced synchronized timetables. Nonetheless, because most PT attributes are stochastic (travel time, dwell time, demand, etc.), their use suffers from uncertainty about the simultaneous arrival of two or more vehicles at a transfer point. Improper or the lack of certain control actions leads to missed transfers, one of the undesirable features of PT service, as it causes increased passenger waiting and travel times and consequently passenger frustration.

Various studies have been advanced to model PT real-time control e.g., (Delgado et al., 2012, 2013, Hadas and Ceder, 2010a, Hickman, 2001, Sun and Hickman, 2005). However, the main drawback of possible real-time control actions is the lack of prudent modeling

and software that can activate these actions, whether automatically, semi-automatically, or manually. In addition, it has been very difficult to evaluate the positive and negative effects of individual control strategies with respect to operations and passenger travel times under real-world conditions (Carrel et al., 2013). Such modeling can be employed in a PT control center in order to allow for the best exploitation of real-time information. Thus, a question arises as to how modeling and simulation can be created to optimally select tactics for real-time operations deployment using the stochastic nature of PT networks. The present work proposes a methodology, based on a robust real-time framework, to find the optimal combination of tactics for controlling the PT system. The objective is to develop intelligent modeling with a library of tactics in terms of real-time control actions; these developments will be based on optimization and simulation frameworks.

### 3.3 Literature Review

Fundamentally there are two distinctive real-time public-transport performance disruptions: 1) deviations from the schedule (timetable), but not necessarily creating an imbalance between supply and demand; 2) creation of an imbalance between supply and demand (overloaded and almost empty vehicles), but not necessarily deviating from the schedule (Ceder, 2007, 2015). Given that these disruptions are known in real-time (e.g., by an automatic data-collection systems and GPS), corrective and restorative control strategies can take place.

Generally speaking, and following Eberlein et al. (1999), control strategies can be divided into three categories: stop control, inter-stop control, and others. The first contains two main classes of strategies, known as holding and stop-skipping. The second category includes such as speed control, traffic signal preemption. The third consists of such strategies as adding vehicles and splitting vehicles. In a follow up study and as an inclusive analytical investigation of the vehicle holding strategy, Eberlein et al. (2001) formulated the holding problem as a deterministic quadratic program and developed an efficient solution algorithm to solve it. At the same time, Hickman (2001) presented a stochastic holding model at a given control station; a convex quadratic program with a single variable was formulated to correspond to the time lapse during which buses were held. A subsequent study by Sun and Hickman (2005) investigated the possibility of implementing a stop-skipping policy for operational control in real-time. A non-linear

integer programming problem for two different stop-skipping policies was formulated to examine how the performance of the two policies changed with the variability of effective parameters on the route.

In terms of new technologies, Dessouky et al. (1999) showed the potential benefits of real-time control of timed transfers using intelligent transportation systems. Continuing along these lines, Dessouky et al. (2003) examined simulated systems that employed holding and dispatching strategies. The results showed that advanced technologies were most advantageous when there were many connecting buses; the schedule slack was then close to zero. Fu et al. (2003) proposed a pair-of-vehicles operational strategy that allowed the following vehicle of a pair to skip some stations. Zhao et al. (2003) proposed a distributed architecture to coordinate bus scheduling at stops using multi-agent systems. The authors treated each bus-stop as an agent; the agents negotiated with one another on the basis of marginal cost calculations to minimize passenger waiting-time costs.

Concerning holding strategy, Zolfaghari et al. (2004) used real-time bus-location information and proposed a simulated, annealing-based heuristic algorithm. Yu and Yang (2009) investigated holding strategy by considering the prediction of next-stop departure times. The support vector machine was used to predict the departure time, and a genetic algorithm employed to optimize the holding time. Cats et al. (2011) proposed a dynamic transit-simulation model, Bus Mezzo, to investigate the holding strategy, considering the interaction of passenger activity, transit operations, and traffic dynamics. Delgado et al. (2012) investigated holding and boarding-limit strategies. A mathematical model without binary variables was proposed for real-time transit operations.

Strategies to increase the efficiency of a high frequency PT route was studied by Daganzo (2009), who showed that without interventions, bus bunching was almost inevitable regardless of the driver's or the passengers' behavior. An adaptive control scheme was analyzed to mitigate the problem. The suggested model dynamically determines bus holding times at route control points based on real-time headway information. Controlling methods using operational tactics to alleviate the uncertainty of simultaneous arrivals was demonstrated by Hadas and Ceder (2008), who developed a new passenger-transfer concept that extended the commonly used single-point encounter (at a single transit stop) to a road-segment encounter (any point along the road-segment constitutes a possible encounter point). Their work has been applied to PT network connectivity in Hadas and Ceder

(2010a). Furthermore, with the aid of operational tactics, Hadas and Ceder (2010b) improved optimal PT-service reliability by means of a dynamic programming approach.

The recent study by Ji and Zhang (2013) also proposed a robust dynamic control strategy to regulate bus headways and to prevent buses from bunching by holding them at bus stops. They developed a controlling method to produce better system reliability than that of some of the existing control strategies. Finally, Muñoz et al. (2013) investigated dynamic control strategies for PT operation with real-time headway-based control, comparing different approaches to different scenarios.

Although extensive research has been conducted to analyze PT movements at a one-way loop transit corridor, only a few analytical studies dealt with real-time PT vehicle control issues at a transit-network level. Thus, there is need to assess and improve service reliability by presenting a proper real-time control algorithm that quantifies the level of system efficiency in more complex systems. In an earlier attempt, Nesheli and Ceder (2014) defined the optimal combination of selected tactics for PT transfer synchronization. A mathematical programming model was formulated to determine the impact of instructing vehicles to either hold at or skip certain stops/segments on the total passenger travel time and the number of simultaneous transfers. They further showed that considering the skip-segment by formulating penalty functions for disadvantaged passengers yielded better results than skipping individual stops. Despite its contribution, their approach had some limitations, mainly related to the assumptions used for constructing the model such as the assumptions associated with passenger demand i.e., passenger demand is independent of vehicle arrival time. The model may need to be further adjusted to account for large errors.

In this work, we overcome these limitations, while preserving and refining the formulations and adding a new operational tactic, short-turning. To the authors' knowledge, the present study provides for the first time in the literature the formulation and implementation of the short-turning tactic as a real-time control action. We develop a hybrid model that uses mixed integer programming (MIP) and constraint programming (CP) techniques to solve the problem, which is a combinatorial problem in which the decision variables are a finite and discrete set. Certainly in order to deal with real-time issues, special attention must be paid to the running time of the algorithm developed. However, because of the problem being NP hard, the proposed method look is to solve the problem in

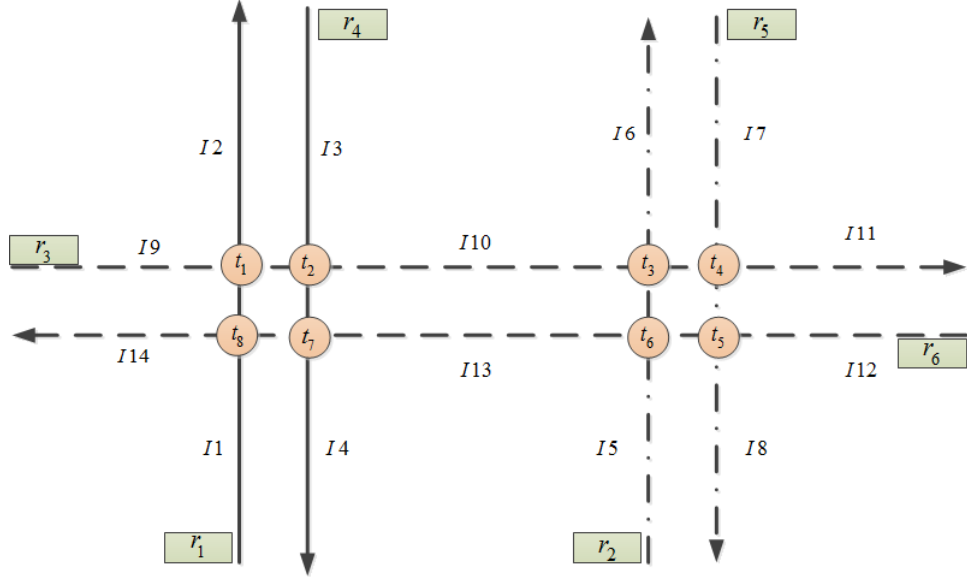
polynomial time to make it tractable. A rolling horizon approach is utilized to solve this hybrid model. An agent-based, transport-simulation framework is also used to represent a real-life example and to generate random input data for the proposed optimization model. Based on the proposed framework, both the uncertainty of the PT service and total passenger travel time are reduced by increasing the number of direct transfers.

### 3.4 System Characteristics

The system underlying the model is a two-way transit network consisting of main and feeder routes. The transfers occur at separate transfer points for each route as shown in Figure 3.1. The service area is divided into  $I1, I2, \dots, Im$  segments (one or more consecutive stops), with  $n \in N$  vehicle stops and  $r \in R$  routes. Vehicles moving on route segments leading to the same transfer points belong to the same rolling horizon scheme. A service is made up of a collection of "trips"; each trip represents a single run, based on a certain departure time, along the series of stops on the route. Vehicles start their run at a terminal, defined as Stop 1, visiting all stops downstream  $2, 3, \dots, n$ . The routes are numbered in strict order of direction along the network; vehicles on routes  $\{r1, r2, \dots, r\frac{|R|}{2}\}$  serve direction 1, and those on routes  $\{r\frac{|R|}{2} + 1, \dots, r|R|\}$ , where  $|R|$  is the size of set  $R$  serving the reverse direction as direction 2. Thus  $\frac{|R|}{2}$  is a size of routes for each direction. The matrix of transfer points  $TF$  where  $t \in TF$  is given, and the matrix of transfer stops is  $TP$ .

The matrix of transfer points involves the routes and their transfer points. The matrix of transfer stops involves the stops and transfer points for the proposed PT system model. Reference stops have been selected, in this work, to help determining the deviation from scheduled arrival times at the transfer points. Thus when a vehicle is arriving at a reference stop, e.g., four stops before the transfer point, the other vehicle could be at a different location than supposed to be according to the timetable. By dividing the other vehicle's route into small segments, the probability of it being present at the location expected can be found. This enables the investigation of vehicle schedule deviation at the stops located before and at the transfer point. Consequently the suggested tactics can then be applied for compensating the schedule deviations.





**Figure 3.1:** Proposed PT system model.

### 3.5 Math Formulation

A new formulation for the problem of transfer synchronization at the operational level with real-time information is considered. This model allows us to improve PT service performance by optimally increasing the number of direct transfers and reducing total passenger travel time. The model describes and explains the conjunction of selected tactics and does not address individual controlling tactics as described in the literature e.g., Delgado et al. (2012, 2013), Sun and Hickman (2005). The main differences between this work and Hadas and Ceder (2010a) are: (i) use of MIP-CP model capable of solving large size problems in comparison with the dynamic programming (DP) approach in Hadas and Ceder work; (ii) use of different methods to implement optimally real-time control actions, and (iii) use of real-world PT network.

#### 3.5.1 Nomenclature

The following indices and parameters are used in the model:

$N$  = Set of stops

$R$  = Set of routes in which  $r, x \in R$ , where  $r$  and  $x$  are two different routes

$Q_r^{max}$  = Passenger capacity of vehicle on route  $r$

$l_r^n$  = Passengers' load at stop  $n$  on route  $r$

$b_r^n$  = Number of boarding passengers at stop  $n$  on route  $r$

$a_r^n$  = Number of alighting passengers at stop  $n$  on route  $r$

$p_{rx}^n$  = Number of transferring passengers from route  $r$  to route  $x$  at stop  $n$

$\lambda_r^n$  = Passenger arrival rate

$\nu_r^n$  = Passengers alighting rate

$d_r^n$  = Vehicle dwell time at stop  $n$  on route  $r$  (in seconds)

$h_r$  = Vehicle headway of route  $r$

$c_r^n$  = Vehicle running time at stop  $n$  on route  $r$  from the previous stop

$A_r^n$  = Vehicle arrival time at stop  $n$  on route  $r$

$D_r^n$  = Vehicle departure time from stop  $n$  on route  $r$

$\Omega(t)_r^n$  = Time penalty function at stop  $n$  on route  $r$

$\Gamma_r^n$  = Time to reach a desired stop-skipped at stop  $n$  on route  $r$

$\theta_r^I$  = Vehicle schedule deviation at segment  $I$  on route  $r$

$E_r^I$  = vehicle elapsed time on route  $r$  from the previous stop to the current position at segment  $I$

$m_r$  = Maximum total number of stops on route  $r$

$U_r$  = Last transfer stop on route  $r$

$k_r^I$  = Positional stop for a snapshot at segment  $I$  on route  $r$

$\omega$  = Ratio between the average speed of a vehicle and the average walking speed of a pedestrian

### 3.5.2 State Variables

Every time a vehicle reaches a reference stop, the model is used to decide how long the arriving vehicle should be held, how many stops should be skipped, and what stops should be turned to serve the opposite-direction demand thus making a direct transfer, based on real-time estimation of the state of the system (i.e., the position of each vehicle and number of passengers aboard) and the number of passengers waiting at the various stops. The state of the system is described by the estimation of the following set of state variables:

$B_r^n$  = Number of passengers for a vehicle departing stop  $n$  on route  $r$

$W_r^n$  = Number of passengers waiting at stops further along route  $r$  and stop  $n$  (future passengers)

$WT_r^n$  = Extra waiting time per passenger at previous stops as a result of the applied tactics

### 3.5.3 Decision Variables

Let  $LT$  be the library of tactics, consisting of holding ( $HO$ ), skip stop/segment ( $S$ ), and short turning ( $SH$ ). To consider the problem of transferring passengers, passenger transfer time ( $T$ ) is defined. The binary variables  $Y$  and  $Z$  are used to determine if a direct transfer is made before and after implementation of tactics, respectively. The term "direct transfer" means a synchronized transfer for vehicles of both routes  $r$  and  $x$  without a wait. The decision variables considered in the model are as follows:

$HO_r^n$  = vehicle holding time at stop  $n$  on route  $r$

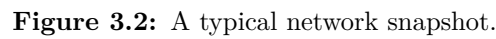
$S_r^n$  = vehicle skipping-stop at stop  $n$  on route  $r$ ; if stop skipped= 1, otherwise= 0

$SH_r^n$  = vehicle short-turning stop at stop  $n$  on route  $r$ ; if stop short-turn= 1, otherwise= 0

$Y_{rx}^n$  = Possible transfer between routes  $r$  and  $x$  at transfer stop  $n$ , pre-tactics; if a possible transfer occurs= 0, otherwise= 1

$Z_{rx}^n$  = Possible transfer between routes  $r$  and  $x$  at transfer stop  $n$ , post-tactics; if a possible transfer occurs= 0, otherwise= 1.





It is assumed that the vehicles are operated in FIFO manner, with an evenly scheduled headway per route. Route information, including travel times between stops, estimation of passenger arrival rates at each stop, and average number of transferring passengers are assumed known and fixed over the period concerned. It is also assumed that passengers onboard a vehicle will be informed of any action at the time of the decision so that they can choose to alight before or after the action. Stops where passengers want to transfer cannot be skipped or short-turned.

We can now formulate a deterministic mathematical programming problem that simultaneously determines holding times, the number of skipped stops from the skipping-stop/segment (skip segment is more general than skip-stop and encompasses it), or short-turning, and lastly the solution for the proposed objective function for each schedule deviation. It is assumed that passengers will wait at their stop until a vehicle arrives (none leaves the system without taking the first vehicle to arrive). Figure 3.2 illustrates a snapshot of a typical 3-route network for clarification. This scheme is showing how to enable vehicles to meet at transfer points. For instance, vehicles of Routes 1 and 3 utilize optimum combination of tactics to meet at the designated transfer point.

### 3.6.1 System parameters

The following equations define boarding, alighting, departure load, and dwell time. It is assumed that passengers arrive at stop  $n$  randomly at a rate of  $\lambda_r^n$ .

$$b_r^n = \lambda_r^n \cdot h_r \quad (3.1)$$

$$a_r^n = \nu_r^n \cdot l_r^{n-1} \quad (3.2)$$

$$l_r^n = \lambda_r^n \cdot h_r - \nu_r^n \cdot l_r^{n-1} + l_r^{n-1} = \lambda_r^n \cdot h_r + (1 - \nu_r^n) l_r^{n-1} \quad (3.3)$$

$$d_r^n = f_0 + f_1 b_r^n \cdot t_b + f_2 a_r^n \cdot t_a \quad (3.4)$$

where  $f_0$ ,  $f_1$ , and  $f_2$  are estimated parameters for the dwell-time function with either  $f_1 = 0$ , or  $f_2 = 0$  based on the input data used; that is  $f_2 = 0$  if the boarding time is longer than the alighting time, and vice versa for  $f_1 = 0$ . The passenger boarding and alighting times are  $t_b$  and  $t_a$ .

### 3.6.2 Holding

The holding problem can be defined as follows: When a vehicle is ready to depart from a station after its normal loading and unloading process, it may be held for a certain amount of time in order to regulate undesired schedule deviations. The problem is to decide which vehicle at a control station at a given time is to be held and for how long, such that the total passenger waiting time is minimized. The holding tactic will affect two groups of waiting time: a) in-vehicle waiting time for passengers on board a vehicle being held at stop  $n$  on route  $r$ ; b) out-vehicle waiting time for passengers waiting for the vehicle further along the route. The components of the holding problem can be written in the following way:

$$B_r^n = l_r^n + b_r^n - a_r^n \quad (3.5)$$

To restrict the number of passengers onboard (capacity-based) when the vehicle departs the stop, the  $B_r^n < Q_r^{max}$  checking constraint is introduced.

For those passengers waiting at stops further along route  $r$  and stop  $n$ :

$$W_r^n = \sum_{j=n+1}^{m_r} \left[ b_r^j + \sum_{x \in R} (1 - Z_{xr}^j) p_{xr}^j \right] \quad (3.6)$$

In-vehicle waiting time for passengers; passenger waiting (PW); aboard a vehicle being held at stop  $n$  on route  $r$  :

$$PW_{r(in-vehicle)}^n = HO_r^n \cdot B_r^n \quad (3.7)$$

Out-vehicle waiting time for passengers waiting for the vehicle further along the route:

$$PW_{r(out-vehicle)}^n = HO_r^n \left\{ W_r^n + \sum_{x \in R} [(1 - Y_{xr}^n) p_{xr}^n - p_{rx}^n] \right\} \quad (3.8)$$

Thus, the holding tactic for the proposed model is formulated as follows:

$$\Delta TPTT(Holding)_r^n = \delta_1 \cdot PW_{r(in-vehicle)}^n + \delta_2 \cdot PW_{r(out-vehicle)}^n \quad (3.9)$$

where each of the two waiting-time components are weighted by  $\delta_1$  and  $\delta_2$ .

### 3.6.3 Skip-stops

In a recent study, Nesheli and Ceder (2014) investigated the formulation and properties of skip-stop/segment with the change in total passenger travel time. It should be noted that "skip-stops" include both skipping tactics: an individual tactic and a segments tactic. That study demonstrated that when a major disruption occurs, holding a vehicle, even if the only tactic available, cannot guarantee obviating headway variation and schedule deviations. This is true even with direct transfers because an individual tactic may result in increased passenger waiting time and lead to missed transfers. According to the assumptions of the present work, passengers on board a vehicle will be informed

immediately of this action at the time of the decision so that they can alight before or after the skipped stops. If the end stop is considered the last stop served before the skipped stops, and the start-again stop the first stop served after the skipped stops, we can define two groups of penalty functions to take into account the drawback of the skip-stops tactic to the passengers' disadvantaged. In first group, passengers who want to alight at the skipped stops and at the end-service stop will have extra time to reach their destination, to be termed "forward time,"  $\Gamma(\text{forward})$ , formulated as follows:

$$\Gamma_{r(\text{forward})}^n = (\omega - 1) \sum_{j=1}^n c_r^j \left( \prod_{j=q}^n S_r^j \right) \quad \forall (n, q \in N) \{1 \leq q < n\} \quad (3.10)$$

where impacted passengers are from stop  $q$  to stop  $n$ , and passengers will not experience vehicle running time.

In second group, passengers alighting at the start-again service stop will need to return to their destination stop, and their time is termed "backward time,"  $\Gamma(\text{backward})$ . Thus, passengers will tolerate additional vehicle running time.

$$\Gamma_{r(\text{backward})}^n = (\omega + 1) \sum_{j=n+1}^{m_r} c_r^j \left( \prod_{j=n}^q S_r^j \right) - \sum_{j=1}^n S_r^j d_r^j \quad \forall (n, q \in N) \{1 \leq n < q\} \quad (3.11)$$

Equations 3.10 and 3.11 build the "walking time" penalty function:

$$\Omega(t)_{r(\text{walking})}^n = \min \left( \Gamma_{r(\text{forward})}^n, \Gamma_{r(\text{backward})}^n \right) \quad (3.12)$$

The alternative to walking is waiting for the next vehicle to bring these passengers to their destination. The waiting time associated with upstream stops is designated  $WT_r^n$ :

$$WT_r^n = \sum_{j=k_r^I}^{n-1} \left( S_r^j d_r^j - HO_r^j \right) \quad (3.13)$$

The "waiting time" penalty function is then determined by the following equation, which takes into consideration the schedule deviation  $\theta_r^I$  which is the time difference between the actual arrival time to a reference stop at segment  $I$  on route  $r$  and the scheduled

(planned, appearing in the timetable) arrival time to this stop:

$$\Omega(t)_{r(waiting)}^n = (h_r - \theta_r^I + WT_r^n) \quad (3.14)$$

Thus, the "total time" penalty function is obtained for the proposed model:

$$\Omega(t)_{r(total)}^n = \min \{ \Omega(t)_{r(walking)}^n, \Omega(t)_{r(waiting)}^n \} \quad (3.15)$$

Consequently, the effect of the skip-stops tactic on the change in the total travel time for route  $r$  and stop  $n$  is formulated as

$$\Delta TPTT(Skip\ Stops)_r^n = S_r^n \left[ a_r^n \Omega(t)_{r(total)}^n + b_r^n \Omega(t)_{r(waiting)}^n - d_r^n (l_r^n + W_r^n) \right] \quad (3.16)$$

#### 3.6.4 Short-turning

Short-turning is another tactic that can be implemented to decrease the irregularity of service and increase the number of direct transfers. When a vehicle is short-turned, a segment of its route is skipped altogether. Unlike the existing literature (Ceder, 1989, Coor, 1997, Cortés et al., 2011, Fürth, 1987, Ulusoy et al., 2010), which implements the short-turning tactic in the planning phase, we use a real-time optimized method in order to assess the potential benefits of this tactic for a network with transfer points. The aim is to offer better service in the opposite direction when demand is greater than in the current direction and passengers need to make transfers. In general, the short-turning tactic may yield large benefits in terms of total cost reductions, whereas it may produce deadheading trips, hence extra cost of running empty vehicles in some sections (Cortés et al., 2011). This tactic can be used for improving real-time performance and responding to unexpected demand; however, it has an adverse effect on on-board passengers. It should be noted that the formulation of the optimization minimizes the number of exposed onboard passengers to the short-turning tactic. In other words, if the number of onboard passengers is large, this tactic will not be implemented.

The real-time short-turning tactic is to decide, at any given time, which stop should be short-turned and how many stops should be skipped by the short-turn vehicle. It is assumed that when the short-turn tactic is put into effect, the vehicle has passed the last

transfer point in the current direction. Short-turning, then, cannot be used if there is any transfer point downstream. The principal output of the model is the change in total passenger travel time for a system with short-turning. Figure 3.2 illustrates the statements.

The main issue in the short-turning formulation problem relates to addressing the opposite stop. If we consider the short-turning stop  $n$  for current route  $r$ , the corresponding stop in the opposite direction of  $r + |R|/2$  could be  $(m_r - n + 1)$ , where  $m_r$  is the total maximum number of stops on route  $r$ . The people disadvantaged by short-turning are those who wanted to alight and those who wanted to board at the stops that are not served (skipped). The assumption is that those passengers who wanted to alight must now walk farther to their destination and that this extra distance is on average the distance between the skipped and the subsequent vehicle stops. The formulation of this type of passengers is detailed as follows:

$$\Omega(t)_{r(\text{waiting})}^n = (\omega - 1) \sum_{j=n}^{m_r} c_r^j \left( \prod_{j=n}^{m_r} SH_r^j \right) \quad (3.17)$$

The alternative to walking is waiting for the next vehicle to bring these passengers to their destination. The waiting time associated with upstream stops is designated by Equation 3.13. The "waiting time" penalty function is then determined by Equation 3.14. Two penalty functions were established: walking time and waiting time, the new definition of "total time" penalty being the lesser of the two as per Equation 3.15. Those who gain an advantage by short-turning are passengers who are currently on the opposite vehicle stop  $b_{r+\frac{|R|}{2}}^{[m_r-n+1]}$  and those who will board the vehicle further along the route:

$$W_{r+\frac{|R|}{2}}^{[m_r-n+1]} = \sum_{j=[m_r-n+1]+1}^{\vartheta_{r+\frac{|R|}{2}}} \left[ \sum_{x \in R} \left( 1 - Z_{\left[x+\frac{|R|}{2}\right]\left[r+\frac{|R|}{2}\right]}^j \right) p_{\left[x+\frac{|R|}{2}\right]\left[r+\frac{|R|}{2}\right]}^j + b_{r+\frac{|R|}{2}}^{[m_r-n+1]} \right] \quad (3.18)$$

The time saving for this group is the headway less the amount of time the vehicle is behind schedule. This saving would be  $h_{r+\frac{|R|}{2}} - \theta_{r+\frac{|R|}{2}}^I$  if no tactics were applied; however, if tactics were applied at previous stops, the wait is formulated as:

$$WT_{r+\frac{|R|}{2}}^{[m_r-n+1]} = h_{r+\frac{|R|}{2}} - \theta_{r+\frac{|R|}{2}}^I + \sum_{j=1}^{[m_r-n+1]-1} \left( S_{r+\frac{|R|}{2}}^j d_{r+\frac{|R|}{2}}^j - HO_{r+\frac{|R|}{2}}^j \right) \quad (3.19)$$

Based on the above equations, the effect of the short-turning tactic on the change in the total travel time with respect to route  $r$  and stop  $n$  can be expressed as follows:

$$\Delta TPTT(Short - Turning)_r^n = SH_r^n \left[ a_r^n \Omega(t)_{r(total)}^n + b_r^n \Omega(t)_{r(waiting)}^n - \left( WT_{r+\frac{|R|}{2}}^{[m_r-n+1]} \times W_{r+\frac{|R|}{2}}^{[m_r-n+1]} \right) \right] \quad (3.20)$$

### 3.6.5 Transfers

Scheduled synchronized transfers so that two or more vehicles can meet at a transfer point can be improved by implementing a library of tactics. Missed transfers will increase total passenger travel time by the extra waiting time for the next vehicle. The waiting time associated with upstream stops is designated by Equation 3.13. Thus, transfer waiting is described as:

$$\Omega(t)_{r(transfer-waiting)}^n = (h_x - \theta_r^I + WT_r^n) \quad (3.21)$$

It is possible to measure the effect of making or missing synchronized transfers on the change in total passenger travel time by the definition of direct transfers. Therefore, a direct transfer occurs if the following holds:

$$Y_{rx}^n + Y_{xr}^n = 0 \quad (3.22)$$

$$Z_{rx}^n + Z_{xr}^n = 0 \quad (3.23)$$

Where a possible transfer  $Y_{rx}^n$  (before the implementing of tactics) occurs if the vehicle departure time on route  $x$  comes after the vehicle arrival time on route  $r$ , and vice versa for  $Y_{xr}^n$ . The same arguments apply to  $Z_{rx}^n$  and  $Z_{xr}^n$  after utilizing tactics. If the following conditions hold, direct transfers will be possible, and none of the vehicles will arrive late at a transfer point:

$$A_r^n = \sum_{j=k_r^I}^n c_r^j - E_r^I \quad (3.24)$$



$$D_x^n = \sum_{j=k_x^I}^n c_x^j - E_r^I + d_x^n \quad (3.25)$$

$$\text{if } D_x^n \leq A_r^n, \text{ then } Y_{rx}^n = 1 \quad \forall (p_{rx}^n + p_{xr}^n \geq 1) \quad (3.26)$$

The real-time transfer problem is formulated as follows:

$$\Delta TPTT (Transfer)_r^n = \sum_{x \in R} \left[ p_{rx}^n \left( Z_{rx}^n \cdot \Omega(t)_{r(\text{transfer-waiting})}^n - Y_{rx}^n (h_x - \theta_r^I) \right) \right] \quad (3.27)$$

### 3.6.6 Objective Function

The objective function of the proposed model can be written as

$$\min \sum_{r \in R} \sum_{n \in N} \Delta TPTT \{ (LT)_r^n + (T)_r^n \} \quad (3.28)$$

### 3.6.7 Constraints

$$S_r^n \left[ \sum_{x \in R} (p_{rx}^n + p_{xr}^n) \right] = 0 \quad (3.29)$$

$$SH_r^n \left[ \sum_{x \in R} (p_{rx}^n + p_{xr}^n) \right] = 0 \quad (3.30)$$

$$A_r^n - WT_r^n - D_x^n - HO_x^n + WT_x^n \leq M * Z_{rx}^n \quad \forall (p_{rx}^n + p_{xr}^n \geq 1),$$

$M \text{ is a large number} \quad (3.31)$

$$A_r^n - WT_{r+\frac{|R|}{2}}^{[m_r-n+1]} - D_x^n - HO_x^n + WT_{x+\frac{|R|}{2}}^{[m_r-n+1]} \leq M * Z_{rx}^n \quad \forall (p_{rx}^n + p_{xr}^n \geq 1) \quad (3.32)$$

$$HO_r^n = 0 \quad \text{when } (n < k_r^I) \quad (3.33)$$



$$S_r^n = 0 \quad \text{when } (n < k_r^I) \quad (3.34)$$

$$SH_r^n = 0 \quad \text{when } (n < k_r^I) \quad (3.35)$$

$$HO_r^n = 0 \quad \text{when } (n > \vartheta_r) \quad (3.36)$$

$$S_r^n = 0 \quad \text{when } (n > \vartheta_r) \quad (3.37)$$

$$S_r^1 = 0 \quad (3.38)$$

$$S_r^n * HO_r^n = 0 \quad (3.39)$$

$$SH_r^n * HO_r^n = 0 \quad (3.40)$$

$$S_r^n * SH_r^n = 0 \quad (3.41)$$

$$HO_r^n \leq \frac{1}{2}h_r \quad (3.42)$$

$$Z_{rx}^n \leq Y_{rx}^n \quad (3.43)$$

$$\prod_{j=n+1}^{m_r} SH_r^j \geq SH_r^n \quad (3.44)$$

$$\prod_{j=1}^{[m_r-n+1]-1} SH_{r+\frac{|R|}{2}}^j \geq SH_r^n \quad \forall \left( r \leq \frac{|R|}{2} \right) \quad (3.45)$$

$$\sum_{j=TP_r^{tr-1}}^{TP_r^{tr}} S_r^j \leq \sum_{tr \in TF} M * Y_{rx}^{tr} \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r^I \right) \quad (3.46)$$

$$\sum_{j=k_r^I}^{TP_r^{tr}} S_r^j \leq \sum_{tr \in TF} M * Y_{rx}^{tr} \quad \forall \left( TP_r^{tr} > k_r^I > TP_r^{tr-1} \right) \quad (3.47)$$

$$\sum_{j=k_r^I}^{TP_r^1} S_r^j \leq M * Y_{rx}^1 \quad \forall \left( TP_r^1 > k_r^I \right) \quad (3.48)$$

$$\sum_{j=TP_r^{tr-1}}^{TP_r^{tr}} SH_r^j \leq \sum_{tr \in TF} M * Y_{rx}^{tr} \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r^I \right) \quad (3.49)$$

$$\sum_{j=K_r^I}^{TP_r^{tr}} SH_r^j \leq \sum_{tr \in TF} M * Y_{rx}^{tr} \quad \forall \left( TP_r^{tr} > k_r^I > TP_r^{tr-1} \right) \quad (3.50)$$

$$\sum_{j=k_r^I}^{TP_r^1} SH_r^j \leq M * Y_{rx}^1 \quad \forall \left( TP_r^1 > k_r^I \right) \quad (3.51)$$

$$\sum_{j=TP_r^{tr-1}}^{TP_r^{tr}} S_r^j * \prod_{tr \in TF} Z_{rx}^{tr} < 1 \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r^I \right) \quad (3.52)$$

$$\sum_{j=K_r^I}^{TP_r^{tr}} S_r^j * \prod_{tr \in TF} Z_{rx}^{tr} < 1 \quad \forall \left( TP_r^{tr} > k_r^I > TP_r^{tr-1} \right) \quad (3.53)$$

$$\sum_{j=K_r^I}^{TP_r^1} S_r^j * Z_{rx}^1 < 1 \quad \forall \left( TP_r^1 > k_r^I \right) \quad (3.54)$$

$$\sum_{j=TP_r^{tr-1}}^{TP_r^{tr}} SH_r^j * \prod_{tr \in TF} Z_{rx}^{tr} < 1 \quad \forall \left( TP_r^{tr} > TP_r^{tr-1} > k_r^I \right) \quad (3.55)$$

$$\sum_{j=K_r^I}^{TP_r^{tr}} SH_r^j * \prod_{tr \in TF} Z_{rx}^{tr} < 1 \quad \forall (TP_r^{tr} > k_r^I > TP_r^{tr-1}) \quad (3.56)$$

$$\sum_{j=K_r^I}^{TP_r^1} SH_r^j * Z_{rx}^1 < 1 \quad \forall (TP_r^1 > k_r^I) \quad (3.57)$$

Constraints 3.29 and 3.30 ensure that the transfer points cannot be skipped. Constraints 3.31 and 3.32 describe whether or not a direct transfer occurs; it confirms that a direct transfer will occur only if the conditions stated are satisfied. Constraints 3.33-3.37 guarantee that the tactics cannot be applied to irrelevant stops (e.g., those not visited or transfer stops already passed by). Constraint 3.38 shows that the first stop may not be skipped. Constraints 3.39-3.41 ensure that no more than one tactic is implemented at the same stop. Constraint 3.42 defines the maximum holding time. Constraint 3.43 ensures that if a transfer is planned for a pre-tactics situation, the same must apply to a post-tactics situation. Constraints 3.44 and 3.45 establish the short-turning tactic in the proper position for each direction. Constraints 3.46 to 3.51 express the condition that if a direct transfer is possible without the use of any tactic, there is no need to interfere, where  $M$  is a large number. Constraints 3.52 to 3.57 describe the non-necessity of tactics if their use does not result in direct transfer.

## 3.7 Model Optimization

### 3.7.1 Optimization Framework

The objective function in Equation 3.28 is linear; however, some constraints are non-linear. The formulation is a combinatorial problem, for which the decision variables are a finite and discrete set. We developed a hybrid model that uses mixed integer programming (MIP) and constraint programming (CP) techniques to solve the problem. CP is an efficient approach to solving and optimizing problems that are too irregular for exact mathematical optimization because (i) the constraints are nonlinear in nature, (ii) a non-convex solution space exists with many local-optimal solutions, or (iii) multiple disjunctions exist resulting in poor returned information by a linear relaxation of the problem (IBM, 2012). The CP technique makes decisions on variables and values and,

after each decision, performs a set of logical inferences to reduce the available options for the remaining variable domains.

In recent years, several studies have showed that an integrated CP and MIP approach can help to solve optimization problems that were intractable with either of the two methods alone (Jain and Grossmann, 2001, Timpe, 2002). The CP and MIP paradigms have strengths and weaknesses that complement each other. CP, through the use of sophisticated propagation techniques, privileges primal inference. On the other hand, MIP, through the techniques of relaxation and strengthening by cutting planes that have been developed for inequality constraints, privileges dual inference (Achterberg et al., 2008). CP methods rely heavily on the application of specialized filtering methods to global constraints and, therefore, must know where global constraints appear in the problem. MIP methods require that inequality constraints appear in the model (Hooker, 2006).

Certainly in order to deal with real-time issues, special attention must be given to the running time of the algorithm developed. However, because the problem is NP hard, the proposed method looks to solve it in polynomial time to make it tractable.

### 3.7.2 Rolling Horizon

Given the real-time, stochastic nature of PT systems, a rolling horizon scheme (a decentralized method) of the control problem was adopted. This means that each time the model solves an optimization problem, it considers only the cooperative segments, which are in the same space horizon that lead to the same transfer point. Such a horizon is rolled forward, and the decentralized process is repeated for each transfer point  $t$  over the entire system. In general, for each transfer point  $t \in TF$

$$\begin{bmatrix} k_r^{Ii} \\ k_x^{Ij} \end{bmatrix} \in Ii \cap Ij \quad \forall (i, j) \in I_m \quad (3.58)$$

where  $k_r^I$  as the positional stop on each route defines its "depth" of computation and can vary at each segment. Figure 3.2 illustrates the statements.

### 3.7.3 Efficiency of the optimization process

The mathematical formulation was coded in OPL using ILOG (IBM, 2012) and implemented on an Intel Core<sup>TM</sup> i5-2500 CPU 3.30 GHZ and 8.00 GB RAM. The execution time of the procedure varies from 3-7 seconds for a proposed PT system model with 133 stops per direction as in the Auckland data. Such a small computation time clearly meets the needs of a real-time control system.

## 3.8 Simulation

Computation of the system-performance measures requires a simulation model with a proper database. The model can be developed with the creation of an agent-based simulation (ABS) for a PT network of routes, operational transit information, and intermodal shortest-path calculation, all of which are to be combined with the computation of the performance of the proposed optimization model. Contrary to traditional simulation methods, ABS uses the activities that create a need for trips (Rieser et al., 2007). An activity usually starts from home and returns home at the end of a whole day's activity. For example, one can have home-work-home as an activity pattern for one day (Rieser, 2004). One or more legs can be defined between two activities. In fact, a leg describes which transportation mode is used to arrive at the next activity. For a bus system, number of legs expresses the number of transfer points that are used to go from one activity to the next. An activity chain consists of a start location  $((x, y) \in O(\text{coordination of origin}))$  and an end location  $((x, y) \in D(\text{coordination of Destination}))$ , plus time information (duration or start/end time), with an activity assigned. For instance, if a person wants to use a PT system between home and work, vehicle-boarding time would be the end-time for the home activity.

### 3.8.1 Simulation Framework

The simulation model is discrete and not continuous. Multi-Agent Transport Simulations (Multi-Agent Transportation Simulation, 2014) provides a framework for implementing agent-based simulations; it offers a mechanism for explicitly connecting activity schedules derived from an activity scheduler with dynamic network models. For a

simulation of the PT system in MATSim, the following data is required (Multi-Agent Transportation Simulation, 2014):

- Configuration file: Specifying the parameters of the simulation and settings, such as scenarios file, events file, strategies file, transit schedules file, vehicles file, population file and network file.
- Multimodal network: A network of links and nodes representing the road and infrastructure of the area. Open street map (OSM) data was used as a source of network attributes.
- Population: A synthetic population of agents, each with attributes and a plan; for this study, AVL and APC data from a local transport agency was used.
- Transit schedule: The schedules for the entire network, with stop locations, departure times, and routes specified. General transit feed specifications (GTFS) provided such a public-transit schedule.
- Transit vehicles file: A description of every type of transit vehicles operating in the PT system, including vehicle specifications, speed, capacity, and length. A local transport agency was used as a source for demand and fleet size.

To complete the simulation and to address the state of a vehicle for all scenarios, different events can be defined to describe the possible status of a vehicle at control stops. In MATSim, events are used to document changes in the state of an object (Multi-Agent Transportation Simulation, 2014). Information on the time of the event, the "*id*" of the agent who caused the event, or the "*id*" of the link where the event happened could be included. This information provides the input of the mathematical programming model, which is solved using a hybrid method solver. The solution will optimize all decision variables related to future control actions, consisting of holding, skip-stops, and short-turning for all vehicle trips. This approach is applied in a rolling horizon framework.

### 3.8.2 Simulation Analysis

*Passenger:* Each passenger's trip time is recorded, including time of generation, time of boarding, and time of alighting. Waiting time, travel time, and door-to-door time can be calculated from this data.

*Travel time:* The travel-time attribute for PT consists of running time, dwell time, and waiting time. Running time is based on the published PT timetables. Assuming that the timetables are realistic, the travel time between two adjacent stops is estimated by averaging the difference between departure and arrival times at these two stops within a specific time window. In the dwelling process, boarding and alighting take place at different doors. In the simulation, each passenger contributes the same marginal time when boarding and when alighting. The total dwell time is then estimated as the maximum time between these two processes. The optimization model assumes a deterministic demand in the simulation, with a short headway; passengers arrive randomly following a Poisson distribution with a mean of  $\lambda_r^n$  at each stop. This distribution is common in services with headways of less than 12 min. (Jolliffe and Hutchinson, 1975, Okrent, 1974). With longer headways, passengers consult schedules to reduce their waiting times and arrive clustered around the departure time. The boarding process follows a FIFO discipline. Thus, the earliest arriving passenger will be the first to board a vehicle if there is available capacity, or will have to wait for the next vehicle if unavailable.

### 3.9 Library of Tactic Frameworks: Combined Tactic-based Problem (CTP)

We found that a combined policy can be justified in many cases where unbalanced demand and uncertainty in travel times within and between directions are observed. When holding is used alone, some vehicles were held much longer than others. Intuitively, skipping- stops tactics may play a role to supplement holding in such a situation. To respond to unexpected demand, adding a short-turning tactic is also beneficial. Both these two stop-skipping tactics will not be used on the same segment of the vehicle trip, because it is unnecessary and would increase passenger frustration. Hence, it is reasonable to assume that a vehicle trip can have at most one skipped segment in a direction, which can be controlled by using one type of control tactic.

What complicates the combined control problem is that a different tactic may be considered for different vehicle trips and different routes within the same impact set (rolling horizon length). Based on research of the hybrid model, the development of an efficient and effective algorithm for this problem becomes quite straightforward. The

logic of this algorithm is basically a robust real-time framework to find the optimal combination of tactics for controlling the PT system.

**Algorithm for CTP** The following CTP-based algorithm generates an optimal combination of tactics for all policies  $\Phi = \varphi_1, \varphi_2, \dots, \varphi_n$  and different scenarios  $\Psi = \psi_1, \psi_2, \dots, \psi_n$ .

**Step 0.** Initial setting: Running the simulation to generate random input data for the proposed optimization model.

**Step 1.** Planned direct transfer (pre-tactics)  $Y_{rx}^n = 0$ , schedule deviation  $\theta_r^I \cong 0$ , and initial control action  $(LT)_r^{I,n} = 0$ .

**Step 2.** Schedule deviation:  $\theta_r^I \neq 0$ , if a direct transfer has not occurred  $Y_{rx}^n = 1$ ; for each  $I \in Im$ , compute the objective function:

$$\min \sum_{r \in R} \sum_{I \in Im} \sum_{n \in N} \Delta TPTT \left\{ \sum_{\varphi \in \Phi} (LT)_{r,\psi_i}^{I,n} + (T)_{r,\psi_i}^{I,n} \right\}.$$

**Step 3.** If in post-tactics a direct transfer occurred  $Z_{rx}^n = 0$ , go to Step 4; otherwise, change the policy  $\varphi$  with a new decision variable and go to Step 2.

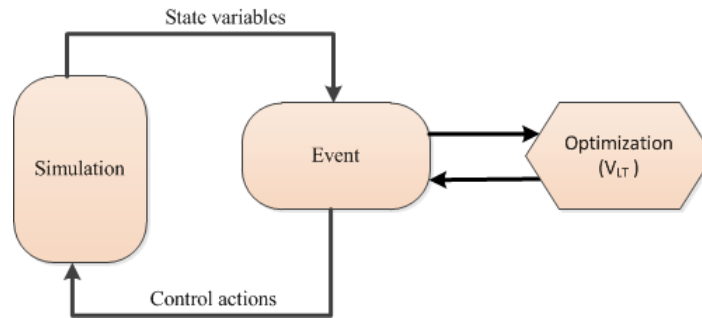
**Step 4.** Verification of the optimum solution by continuing the simulation: If the solution has an acceptable confidence interval (difference between the results of simulation and optimization), stop; otherwise, change the policy  $\varphi$  with new a decision variable and go to Step 2.

Based on the CTP algorithm, the value of suggested tactics ( $V_L T$ ) is determined.  $V_L T$  denotes the optimal value of a tactic for each scenario. This optimal solution will naturally tend to maximize the number of direct transfers and the potential saving in total passenger travel time. This approach is entitled 'optimization- and simulation-based' as opposed to the results of the optimization only entitled 'optimization-based'. Figure 3.3 illustrates the general analysis of the CTP framework.

### 3.10 Case Study

The analysis carried out was based on a case study of Auckland, New Zealand, the country's largest and busiest city, whose PT system has been criticized for not being

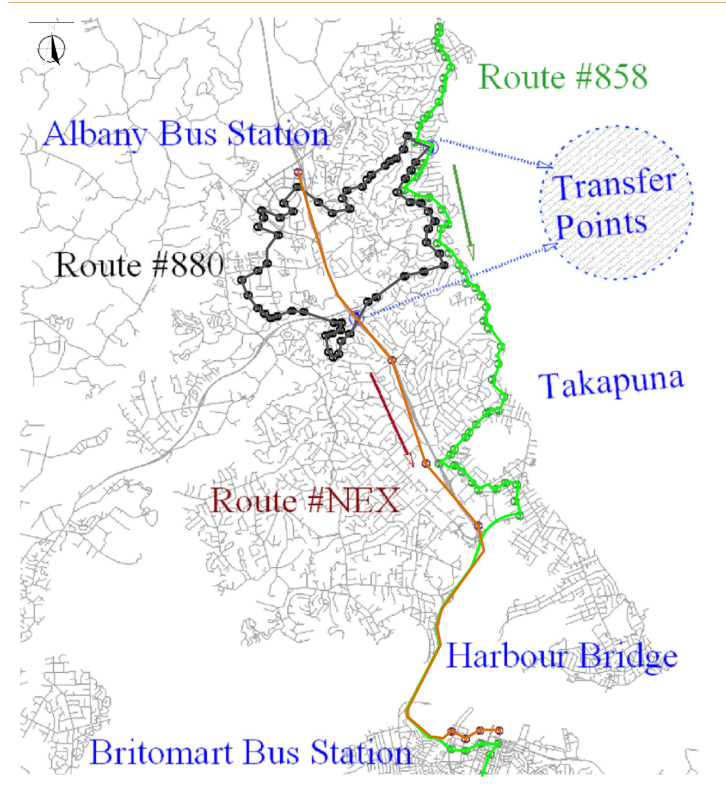




**Figure 3.3:** CTP framework.

efficient (Mees, 2010). More recently, the Auckland Transport Regional Public Transport Plan (AT, 2013) was created for the purpose of developing an integrated transport network to provide Aucklanders with a sustainable transport system in a safe, integrated, and affordable manner. This plan shows the intensive discussion conducted on various issues relating to PT systems of the future; indeed, a major focus over the next decade will be the enhancement of the PT system. Thus, there is need to investigate the performance of Auckland's PT system. A case study for the Auckland region was based on AT (Auckland Transport) data, which consisted of the PT network, AT- HOP cards (Auckland Integrated Fares System), OD pairs, and a PT demand forecast. It is to note that all buses of the Auckland transport network are equipped with AVL systems. The AVL data are used to analyze bus travel times and schedule adherence (to implement holding tactics). This means that real-time information on bus locations can be used to predict bus arrivals at the transfer points and to determine bus schedule deviations.

The PT network data is based on the AT transit feed dated May16, 2014. Analysis was carried out on three bus routes and two transfer points. It should be noted that by considering both directions, there is a total of 8 transfer possibilities. The first route, known as Northern Express (NEX), has a dedicated lane that runs from the suburbs to and across the Auckland CBD area; it transports a very large number of passengers during peak hours. The second route, Route 858, runs north-south (east of the first route); and the third route, Route 880, is a loop that serves as a feeder route. Observation shows that peak hours during the morning are 7-9 a.m., and during evening 4-6 p.m. A higher demand is observed from suburbs to CBD during the morning and the reverse in the evening. Figure 3.4 illustrates the bus system and study routes.



**Figure 3.4:** Auckland, NZ, bus system and study routes.

### 3.10.1 Scenarios

As summarized in Table 3.1, fourteen scenarios were tested to evaluate and compare the proposed model under different operational conditions. These scenarios differ in two dimensions: (i) bus schedule-deviation (event) for different bus states; (ii) service headways, which can be high frequency services (i.e., short headways), or low frequency services (i.e., long headways). These scenarios present the combined effect of the major attributes of a PT service on the model.

### 3.10.2 Control Strategies (Policy)

We tested and compared four different control policies. The first policy, "No-Tactics," was used for comparison purposes. The second was the combination of "Holding and Skip-Stops". The third was the combination of "Holding and Short-Turning". The last policy was a combination of the three tactics modeled.

**Table 3.1:** List of scenarios

Scenario	Event (sec)	Headway
1	$-100 > \theta$	Short
2	$-100 \leq \theta < -55$	Short
3	$-55 \leq \theta < -20$	Short
4	$-20 \leq \theta < 20$	Short
5	$20 \leq \theta < 60$	Short
6	$60 \leq \theta < 110$	Short
7	$110 \leq \theta$	Short
8	$-100 > \theta$	Long
9	$-100 \leq \theta < -55$	Long
10	$-55 \leq \theta < -20$	Long
11	$-20 \leq \theta < 20$	Long
12	$20 \leq \theta < 60$	Long
13	$60 \leq \theta < 110$	Long
14	$110 \leq \theta$	Long

### 3.10.3 Simulation Parameters

The marginal burden or disutility of out-of-vehicle waiting time is perceived to be significantly more burdensome than in-vehicle travel time (Reed, 1995). Thus, the weighting factors were set to  $\delta_1 = 1$  and  $\delta_2 = 2$  to reflect in-vehicle and out-vehicle waiting times, respectively. Boarding and alighting times per passenger were set at 2.5 and 1.5 seconds, respectively. Vehicle capacity was given as 60 passengers, with 40 seated and 20 standing.

**Synchronized timetables:** One of the main assumptions for the model was that the PT network was synchronized (at the planning stage); the objective of the optimization process was to attain a better synchronization, considering the changes in travel times that might result from traffic congestion or changes in passenger demand. Hence, the simulation model was executed with a synchronized timetable (Table 3.2). Table 3.2 also shows the average number of passengers per simulation on each route.

**Transfer points:** The matrix of transfer points described the points of planned transfers along the routes. It should be noted that  $\{r1, r2, r3\}$  address direction 1 and  $\{r4, r5, r6\}$  refer to direction 2. The transfer matrix is presented in Table 3.3.

**Table 3.2:** Route characteristics

Route	First Departure	Headway (min.)		Average number of passengers	
		Short	Long	Short	Long
1	6:00	5	15	896	702
2	6:15	10	20	3,384	3,258
3	6:15	5	15	2,754	2,142

**Table 3.3:** Matrix of transfer points

TF	r1	r2	r3	r4	r5	r6
r1	0	0	$t_1$	0	0	$t_8$
r2	0	0	$t_3$	0	0	$t_6$
r3	$t_1$	$t_3$	0	$t_2$	$t_4$	0
r4	0	0	$t_2$	0	0	$t_7$
r5	0	0	$t_4$	0	0	$t_5$
r6	$t_8$	$t_6$	0	$t_7$	$t_5$	0

### 3.11 Analysis

The performance of the Auckland system was evaluated by means of total passenger travel time. The events were extracted from the simulation model for 24 hours. For each trip, the states of the bus with reference to different events at selected control stops were computed. Based on optimization, the maximum hold time observed in all scenarios was 186 seconds, subject to the length of headways, and the average hold time was 41 seconds. Table 3.4 summarizes the main results of the performance indicators, an analysis of which follows:

**Total passenger travel time:** The total passenger travel time (travel time and waiting time) was computed for all passengers completing a trip from origin to destination.

**Direct transfers:** The CTP algorithm was determined for each scenario so as to minimize total passenger travel time; this optimal solution will naturally tend to maximize the number of direct transfers. Direct transfers were analyzed in terms of the number of transfers.

**Table 3.4:** Summary of the results

Average Improvement	Headway		Control Policy		
	Short	Long	HO+S	HO+SH	HO+S+SH
TPTT (%)	3.61	2.37	2.14	2.10	4.73
DT (%)	249.55	182.19	101	103	153
Note: HO = holding; S= skip-stops; SH= short-turning.					

**Improvement:** Different policies were compared in terms of total passenger travel time and direct transfers.

From the Table 3.4 summary, it is possible to draw an immediate conclusion that applying the library of selected tactics improved overall system performance. The short headways yielded the best results, as expected. The results revealed that the CTP process does improve system performance considerably by the use of different policies in various scenarios. The combination of all possible tactics leads to the highest improvement in the objective function of the proposed model. CTP shows significant benefits in relation to Holding and Skip-Stops and Short-Turning in all scenarios. Interestingly, with this control policy, not only is the expected total passenger travel time reduced (on average by 4.73%) in comparison with a no-control policy, but it also outperforms other control schemes in terms of reliability in meeting vehicles at transfer points. Thus, combination of all the control tactics leads to an increase in direct transfers of up to 153% on average for all scenarios. Table 3.5 describes the total passenger travel time and the number of direct transfers for each scenario with each of the four types of control policies. The last column of this table presents the percentage improvement of each combined tactic over the No-Tactics ("None") policy. The results demonstrate the significantly better performance of the fourth policy, the combination of all tactics, in all scenarios. This can be observed graphically in Figure 3.5, which illustrates the effect of the model on total passenger travel time and on number of direct transfers. Generally the results also show a somewhat superior outcome for the holding and skip-stops policy than for holding and short-turning, with a 2.14% and 2.10% improvement in total passenger travel time, respectively. However, Figure 3.5 shows that the holding and short-turning policy for a larger schedule deviation results in a better performance than the holding and skip-stops strategy. This indicates that applying such a combination of tactics in

worse scenarios leads to considerable progress in PT service.

In terms of scenario, Table 3.5 and Figure 3.5 demonstrate greater service enhancement through a reduction in total passenger travel time in scenarios with short headways (#2 and #3) and long headways (#10 and #12). This suggests that if the deviations are reasonable, the use of tactics can save travel time and increase the number of direct transfers drastically. It also indicates that unreliable service owing to long delays cannot be compensated properly by the use of tactics, since more passengers will have to wait for the next bus or find alternative solutions (as may be observed in scenarios #1, #7, #8, and #14). Figure 3.5 shows that when the schedule deviation tends to zero, as in scenarios #4 and #11, the maximum number of direct transfers, using tactics, coincides with the minimum system's fluctuations; this maximum travel time saving coincides with the maximum number of direct transfers. This finding corroborates the authors' previous study (Nesheli and Ceder, 2014).

As the aim of the implementation of tactics was mainly to synchronize the arrival of transit vehicles at a transfer area, the results show a significant improvement in the number of direct transfers resulting from the use of control policies. Again, the short-headways scenarios yielded the best results as expected. It may also be observed from Figure 3.5 that with large schedule-deviation intervals, control policies contribute to a higher percentage of direct transfers. As Table 3.5 shows, the greatest reductions in the objective function are achieved in high-frequency scenarios in which buses experience reasonable schedule deviations; here, time savings may amount to 10.6% more than what is achieved with the no-control strategy, and direct transfers may improve by as much as 830%.

Table 3.5: Main simulation results

Scenario	Control Policy	simulation				Optimization					
		TPTT[sec]		DT		Improvement		TPTT[sec]		Percentage	
		Total Passenger	Direct	Direct	Direct	Transfer (%)	TPTT (%)	Reduced	Increased	Reduced	Increased
		travel Time	Transfer	Transfer	Transfer	Transfer	Transfer	Time	Time	Time (%)	Time (%)
1	None	445066.04	10								
	HO+S	435803.09	41	310	2.1			14772.16	4917.96	3.32	1.24
	HO+SH	434386.90	51	410	2.4			16074.46	4950.36	3.61	1.25
	HO+S+SH	426998.08	83	730	4.1			24997.98	5143.08	5.62	1.30
	None	445066.04	20								
2	HO+S	425739.47	141	605	4.3			24946.54	5022.24	5.61	1.27
	HO+SH	424340.12	143	620	4.7			22460.04	5188.44	5.05	1.31
	HO+S+SH	398844.17	186	830	10.4			54116.52	5461.92	12.16	1.38
	None	445066.04	53								
3	HO+S	428814.37	155	192	3.7			21502.94	4748.64	4.83	1.07
	HO+SH	431795.18	139	162	3.0			19213.6	4468.2	4.32	1.00

4	HO+S+SH	397998.36	192	262	10.6	47374.72	4585.92	10.64	1.03
	None	445066.04	156						
	HO+S	440682.32	184	18	1.0	5496.3	1511.1	1.23	0.34
	HO+SH	442221.83	178	14	0.6	4746.8	1621.3	1.07	0.36
	HO+S+SH	438411.39	202	29	1.5	9167.3	1854.5	2.06	0.42
5	None	445066.04	86						
	HO+S	430738.27	175	103	3.2	17067.06	3421.56	3.83	0.77
	HO+SH	433842.08	168	95	2.5	15810.18	3055.68	3.55	0.69
	HO+S+SH	414762.17	211	145	6.8	35939.76	3354.96	8.08	0.75
	None	445066.04	64						
6	HO+S	435611.43	136	113	2.1	11836.4	3615	2.66	0.81
	HO+SH	435661.32	130	103	2.1	13967.96	3855.36	3.14	0.87
	HO+S+SH	422119.13	144	125	5.2	25848.88	3994.68	5.81	0.90
	None	445066.04	31						
	HO+S	439708.88	49	58	1.2	10177.84	4225.44	2.29	0.95
7	HO+SH	439278.84	51	65	1.3	10529.84	4307.04	2.37	0.97



8	HO+S+SH	431365.62	69	123	3.1	18754.82	4333.32	4.21	0.97
	None	486369.56	6						
	HO+S	483222.22	19	217	0.6	9245.82	5824.8	1.90	1.20
	HO+SH	482325.66	21	250	0.8	9267.04	5054.64	1.91	1.04
	HO+S+SH	479622.79	27	350	1.4	12693.6	5439	2.61	1.12
9	None	486369.56	12						
	HO+S	477200.50	52	333	1.9	15164.64	5305.4	3.12	1.09
	HO+SH	475478.17	59	392	2.2	16279.6	4934.4	3.35	1.01
	HO+S+SH	464515.14	81	575	4.5	26718.5	5292.6	5.49	1.09
	None	486369.56	53						
10	HO+S	470732.51	109	106	3.2	18440.94	4225.44	3.79	0.87
	HO+SH	474645.36	112	111	2.4	16886.1	4142.4	3.47	0.85
	HO+S+SH	452182.10	123	132	7.0	40332.24	4345.44	8.2	0.89
	None	486369.56	91						
	HO+S	480816.98	119	31	1.1	7581.1	1856.8	1.56	0.38
11	HO+SH	480897.77	116	27	1.1	6965.43	1754.2	1.43	0.36

12	HO+S+SH	477194.92	153	68	1.9	11838.2	1973	2.43	0.41
	None	486369.56	67						
	HO+S	472928.66	121	81	2.8	18599.48	4742.88	3.82	0.98
	HO+SH	475772.97	119	78	2.2	15779.34	4625.04	3.24	0.95
	HO+S+SH	469366.98	141	110	3.5	24328.2	4785	5.00	0.98
13	None	486369.56	43						
	HO+S	476723.07	81	88	2.0	14539.24	4385.04	2.99	0.90
	HO+SH	472889.83	96	123	2.8	16168.7	3914.4	3.32	0.80
	HO+S+SH	462303.68	105	144	4.9	29557.94	4225.44	6.08	0.87
	None	486369.56	11						
14	HO+S	482706.54	28	155	0.8	8974.82	4949.52	1.85	1.02
	HO+SH	480636.58	41	273	1.2	9444.8	4233	1.94	0.87
	HO+S+SH	479480.33	61	455	1.4	13159.1	5504.4	2.71	1.13

Because of the nature of the optimization, not all passengers necessarily experience a decrease in total travel time. Table 3.5 summarizes the effect of each policy in terms of passengers' total travel time.

**Reduced time:** The reduced time of passengers (in time units or percent) when using tactics.

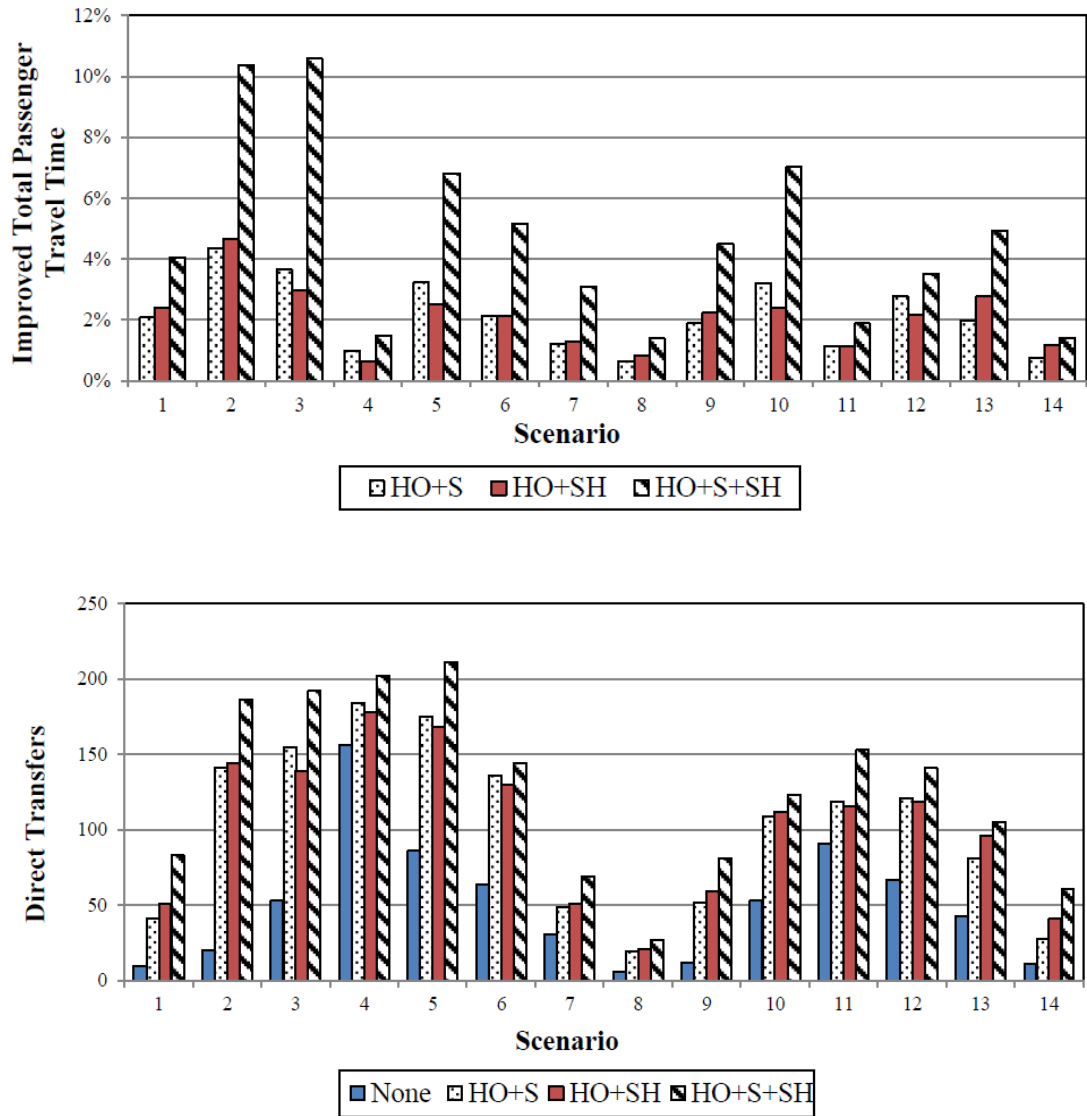
**Increased time:** The time (or percentage) of passengers experienced increased travel time when using tactics.

The results demonstrate that the increase in passenger travel time is usually less than 1%. This shows the real potential of the model for deployment in real life. Figure 3.6 also shows that higher percentages are attained in scenarios #1, #2, #8, and #14, in which passengers experience extra waiting time owing to larger schedule deviations. The worst scenario involves a long headway, scenario #8, in which the schedule deviation is large and the bus is considerably behind schedule. As expected, the maximum reduced time is for short headways as in scenarios #2 and #3.

**Optimization type:** Global and local optimizations were compared in terms of total passenger travel time saved. Figure 3.7 depicts the gap between the global and sub-optimal solutions for the last control policy. Minimum gaps are attained for scenarios characterized by a small schedule deviation, for scenarios #4, #5, #10, and #11 in Figure 3.7. That is, the maximum number of direct transfers, using tactics, coincides with the minimum system's fluctuations.

### 3.12 Conclusions

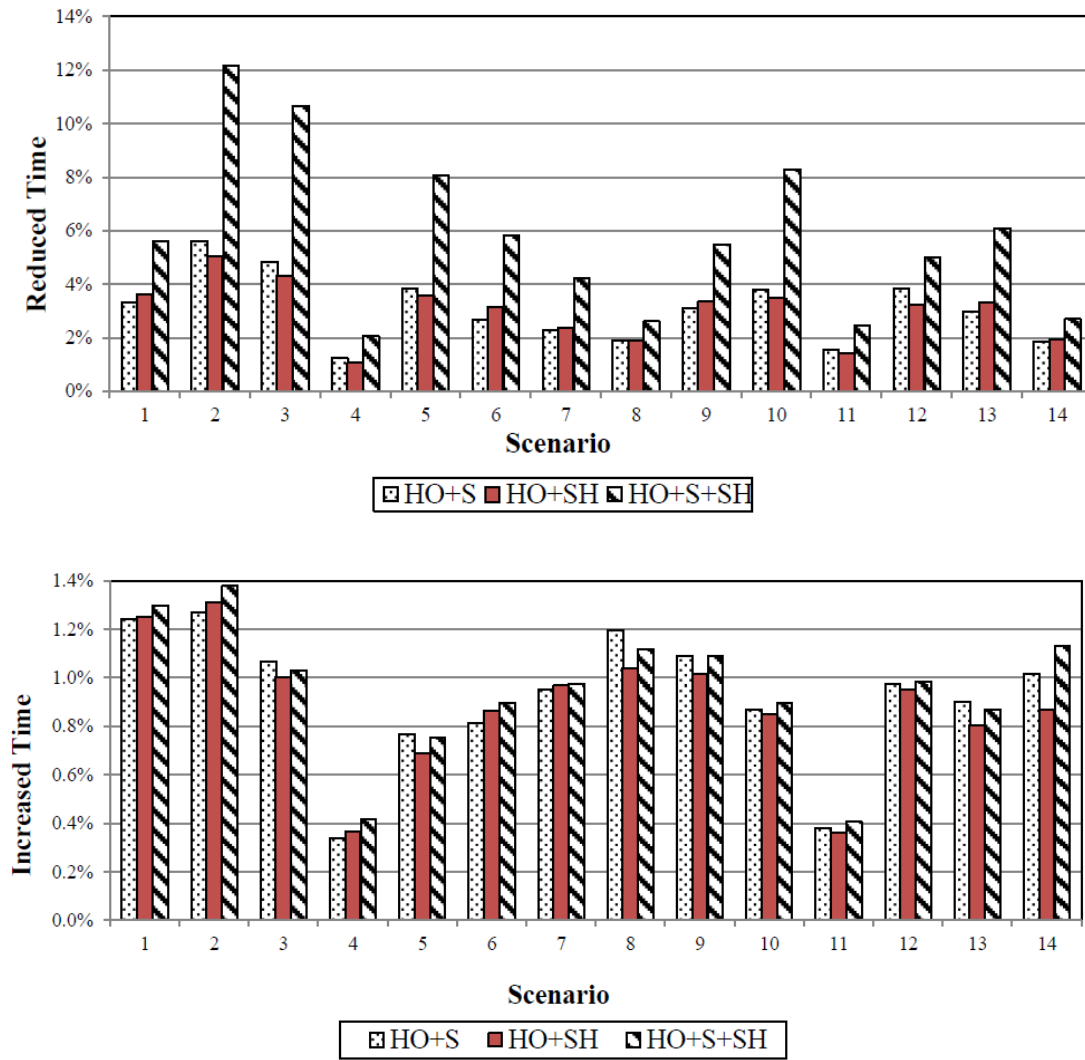
It is a common phenomenon that synchronized transfers of PT networks do not always materialize, because of uncertain and unexpected factors, such as traffic disturbances and disruptions, unexpected demand, and inaccurate driver actions. As a result, missed transfers not only frustrate existing passengers, they will also cause the loss of potential new users (Ceder et al., 2013a). In order to implement measures that will effectively encourage the use of routes with transfers, it is essential to develop operational tactics and strategies for minimizing passenger travel time and for approaching the ideal of direct transfers without waiting. Such a condition will undoubtedly make PT service



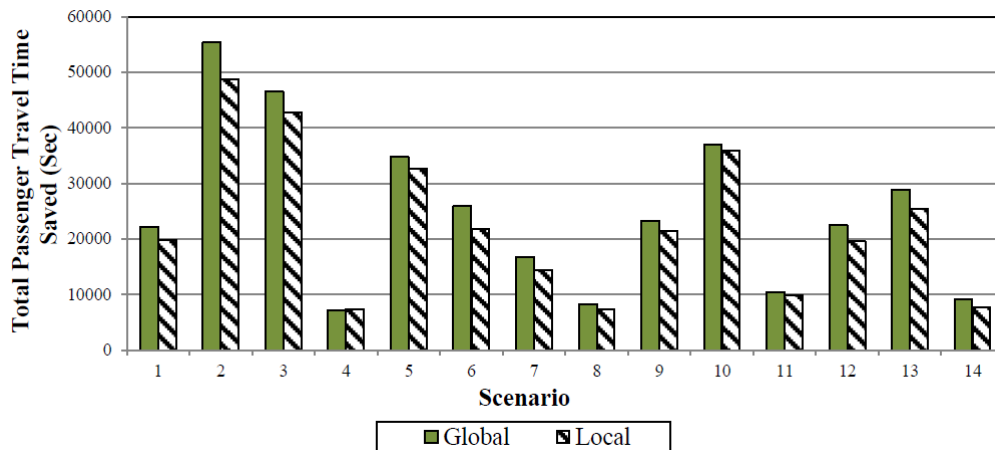
**Figure 3.5:** Total passenger travel time saved, and number of direct transfers per scenario

more attractive. In this study, besides the improvement of the reliability of the PT system through seamless transfers, the effect of each tactic on system performance was investigated. System reliability is represented by schedule deviation, which was calculated at control stops across all bus trips. Lower schedule deviation results in lower passenger waiting times and indicates greater system reliability. System efficiency is represented by the effect of different tactics on each bus trip for different events.

In this paper, we presented original mathematical programming formulations for three real-time control strategies, or policies: holding, skip-stops, and short-turning. This is the



**Figure 3.6:** Reduced and increased total passenger travel time per scenario



**Figure 3.7:** Total passenger travel time saved per scenario.

first time that short-turning has been applied in real-time control action. Short-turning will help bring about better service in the opposite direction if demand there is more than in the current direction and passengers need to make a transfer. Passenger's extra waiting time will be decreased by this tactic. Furthermore, by adding it to the library of tactics, we can decrease the number of vehicles needed to provide a given frequency (Ceder, 1989). This tendency is welcome because it brings at one and the same time more benefits and less frustration to passengers, especially on high-frequency services.

The proposed model was evaluated in a stochastic simulation environment under different schedule-deviation conditions (events) that could highlight when control policies improve the system's performance. An agent-based simulation framework was built to represent a real-life example and to generate random input data for the proposed optimization model. Based on the formulations for optimization and the simulation framework, we developed an efficient algorithm for combining all control actions selected. The algorithm (CTP) is basically a robust, real-time framework for finding the optimal combination of tactics to control the PT system. This work examined four policies-"No-Tactics", "Holding and Skip-Stops", "Holding and Shot-Turning", and a combination of the three possible operational tactics in fourteen scenarios. These scenarios covered a wide range of schedule deviations as events.

The computational results demonstrate that the effectiveness of combined tactics is higher than that of any binary type of control. Based on the proposed framework, both the uncertainty of the PT service at transfer points and total passenger travel time were reduced by increasing the number of direct transfers. This result has a huge effect on the comfort of the ride and ease of transfer, as passengers spend less time waiting at a bus stop and experience smoother multi-legged rides.

CTP shows significant benefits in relation to the Holding & Skip-Stops & Short-Turning tactics in all scenarios. Interestingly, not only is the expected total passenger travel time reduced (on average by 4.73%) by this control policy compared with a no-control policy, but it also outperforms other control schemes in terms of reliability in meeting vehicles at transfer points. Thus, combining all control tactics leads to an increase in direct transfer of up to 153% on average for all scenarios. In addition, the results demonstrate that (i) the short headways yield the best results, compared with long headways; (ii) a considerable reduction in total travel time is attained in scenarios

having no large schedule deviations; (iii) a Holding and Short-turning policy in a larger schedule-deviation scenario exhibits better performance than does a Holding and Skip-Stops policy; (iv) the increase in passenger travel time stemming from the use of operational tactics is usually less than 1%.

Future research, on which the authors have already been working, includes validation of some of the assumptions made, new control measures to develop the library of operational tactics especially with the advancement of communication technologies, the utilization of sensitivity analysis of different tactics, the introduction of a decision-support tool to provide information before implementing any control actions (controlling demand side), and weighting the quality of transfers in an optimization model for different transfer types.

The next chapter introduces a new PT performance index and deterioration and improvement patterns to improve the reliability of PT in real-time.

## Chapter 4

# Improved Reliability of Public Transportation Using Real-Time Transfer Synchronization

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(Nesheli and Ceder, 2015a)

### 4.1 Abstract

Service reliability of public transportation (PT) systems is a dominant ingredient in what is perceived as the PT image. Unreliable service increases the uncertainties of simultaneous arrivals of vehicles at a transfer point. Implementing proper control actions leads to preventing missed transfers, one of the undesirable features of PT service and a major contributor to a negative image. The present work focuses on performance measurements of a PT system offering direct transfers on multi-legged trips. The method developed evaluates and improves system performance by applying selected operational tactics in real-time scenarios. In order to investigate the efficiency level of the PT system, five types of vehicle positional situations with reference to a transfer point are considered: considerably ahead of schedule, ahead of schedule, on schedule, behind schedule, and considerably behind schedule. Each situation contributes differently to



the degree of system performance. The optimization framework developed results in selected operational tactics to attain the maximum number of direct (without waiting) transfers and minimize total passenger travel time. The implementation of the concept is performed in two steps: optimization and simulation. The optimization process searches for the best operational tactics, using the states of the five vehicle-position types, and the simulation serves to validate the optimal results under a stochastic framework using the concept of a multi-agent system. A case study of Auckland, New Zealand, is described for assessing the methodology developed. Results showed a 58% improvement in the system performance index compared to no-tactic operations.

## 4.2 Introduction

A public transportation (PT) system has two major phases: planning and operation. The first phase aims at designing routes; time tables, synchronized transfers, and timed transfers that improve the planned transfers on the basis of a priori data (Ceder, 2007, 2015). Synchronized transfer studies are described by Wirasinghe and Liu (1995) and Ceder and Tal (2001), and the timed-transfer concept is described by Maxwell (1999). The second phase aims at improving PT service reliability using real-time data. Therefore, the question arises as to whether remedies exist to service reliability problems and, if so, whether they are implementable and comprehensive. The present research assumes that planned transfers exist (as part of the first phase); however, with a continuous flow of real-time data, there is need to select tactics that will attain the minimum discrepancy between planning and operations.

Generally speaking, PT agencies have adopted a common tactic of developing an integrated, effective multi-modal transport system in order to provide travelers with a reliable alternative to private cars. An important step in the development of an integrated system is for policy-makers and transit operators to facilitate routes with "seamless" transfers. Therefore, in order to retain existing users and attract new passengers, the main idea in the development of an integrated PT system is to improve the serviceability of routes with transfers. Ceder (2007, 2015) shows that an attractive, advanced PT system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, constitutes part of the door-to-door passenger chain. Levinson (2005) demonstrates that reliable transit service is essential to attracting and retaining riders, principally in

modern societies, which make available many transportation options. Balcombe et al. (2004), in a practical UK transit guide, report that in passengers' perception, the service reliability of local bus services is considered twice as important as frequency.

Because of the fact that most public transit attributes (travel time, dwell time, demand, etc.) are stochastic, the passenger is likely to experience unplanned waiting and trip times. Vincent (2008) shows that transit passengers perceive unexpected waiting time to be 3 to 5 times as burdensome as in-vehicle time.

In regard to transfer reliability, one efficient approach to alleviate the uncertainty of the simultaneous arrival of vehicles to a transfer point and to correct schedule deviations is to use selected operational tactics, such as holding, skip-stop, and short-turn. Studies (Ceder et al., 2013b, Hadas and Ceder, 2010a, Nesheli and Ceder, 2014) show that by applying some operational tactics, the number of direct (simultaneous) transfers can be increased significantly and total passenger travel time reduced. This study utilizes a different perspective and modeling of optimal combination of PT operational tactics than Nesheli and Ceder (2014).

In an inclusive analytical investigation of vehicle holding strategy, Hickman (2001) presents a stochastic holding model at a given control station. A follow-up study by Sun and Hickman (2005) investigates the possibility of implementing in real-time a stop-skip policy for controlling operations. In regard to new technologies, Dessouky et al. (2003) examine simulated systems employing holding and dispatching strategies. They also examine the dependence of system performance on new technologies by combining advanced PT systems with the use of an intelligent transportation system (ITS), such as AVL, APC, and wireless communication, to accurately forecast estimated bus arrival times and to coordinate transfers by means of bus-holding strategies. Daganzo (2009), in studying strategies to increase the efficiency of a high-frequency PT route, followed Daganzo and Pilachowski (2011) who show that bus bunching is almost inevitable without intervention, regardless of the drivers' or the passengers' behavior.

The recent study by Ji and Zhang (2013) also proposes a robust dynamic control strategy to regulate bus headways and to prevent buses from bunching by holding them at bus stops. They develop a controlling method to produce better system reliability than do some of the existing control strategies. Finally, Muñoz et al. (2013) investigate

dynamic control strategies for PT operation with real-time headway-based control. They compare different approaches with different scenarios.

To date, the main drawback of possible real-time control actions is the lack of prudent modelling and software that can activate these actions, whether by automatic, semi-automatic or manual mode. Such a system can be employed in a PT-control center to allow for the best exploitation of real-time information. Thus, there is need to assess and improve service reliability by presenting a proper performance indicator that quantifies the level of system efficiency. This study introduces a new indicator: the average additional travel time per passenger; it is the average extra time required for passengers to travel from origin to destination because of service unreliable and inefficient service. For the analysis performed a model is developed to calculate the effect of real-time operational tactics on passenger travel time. One of the outstanding aspects of this study is using agent-based modeling for simulation in order to incorporate more prudent condition of real-life scenarios.

In this work, Section 4.3 describes the PT service's reliability characteristics. This section comprises three main parts (i) definition of real-time situation type, (ii) determination of optimal control actions required for operational tactics, and (iii) agent-based modeling for simulation. Section 4.4 constructs a model for system performance indicator. Firstly the properties of a PT system are introduced. A knowledge of system's properties linked to a stochastic environment is required to investigate precisely the process of system deterioration. Afterward, the system performance indicator model is developed. Section 4.5 analyses the methodology. Section 4.6 describes a case study in Auckland, New Zealand. Section 4.7 discusses the findings and results including a sensitivity analysis. Lastly, Section 4.8 summarizes the finding and conclusions.

*Objective:* The objective of this work is to develop a system reliability model to measure and improve the reliability of PT service performance in real-time. This study investigates how to utilize the optimal combination of operational tactics for controlling the PT system. Thus, the main objective of the research is quantifying the level of system efficiency by presenting a proper performance indicator. The state of vehicles affects the PT system insofar as missing or making a direct transfer and reducing the total passenger travel time. Therefore, the first step was to categorize the state of vehicles at their possible locations before the transfer point. The second step was to evaluate

the implementation of the selected tactics of the PT system in real-time and to develop performance indicators. Such performance indicators also reflect the influence of each control action on the quality of service.

### 4.3 Public Transport Service-Reliability Characteristics

The more easy, comfortable, and synchronized transfers are, the more attractive a PT system is. For any PT system, as with other systems, reliability can be defined as the probability that a transport service will perform a required function under given environmental and operational conditions for a stated period of time (Iida and Wakabayashi, 1989). To evaluate the impact of a PT system on the passengers' attitude and to present a control method to enhance service reliability, a system-performance indicator should be defined. Generally the analysis can be carried out in four phases: (i) real-time vehicle situation type classification, (ii) optimal tactics derivation, (iii) agent based-modeling for simulation, and (iv) calculation of system-performance indicators. It is worth mentioning that the developed agent-based modeling depicts a more realistic environment than a previous work done by Nesheli and Ceder (2014).

#### 4.3.1 Real-time Situation Types-states

Since buses move in a network, a bus may be placed in a particular location on a route. The notion of reference stops is introduced to determine deviations from scheduled arrivals at the transfer points, thus enabling an investigation of schedule deviations at stops located before, as well at a transfer point. Consequently, the suggested tactics can be applied to compensate for schedule deviations. For example, when a bus on route  $r_1$  arrives at a reference stop, the bus on route  $r_2$  could be at one of many different locations. Information about the buses in each case will serve as input for the optimization model. An optimal tactic-related scenario will be suggested for each case of schedule-deviation so as to minimize total passenger travel time; this optimal solution will tend naturally to maximize the number of direct transfers. In order to cope with the dynamic, stochastic and uncertain nature of the PT system, it is possible to categorize schedule deviations into five states.

**State 1:** *Being considerably ahead of schedule:* Because of external interruptions or uncertainties, a vehicle may sometimes move ahead of its expected schedule time. If this happens, passengers may miss their vehicle either at the stop or at a transfer point and, therefore, have to wait for a complete headway. Some control strategies, such as holding or changes in speed, can be employed to reduce situations of unreliable service. However, as is shown by the optimization and simulation results, no control action is applicable when the schedule deviation is large.

**State 2:** *Ahead of schedule:* If the deviations are reasonable, and not like those of State 1, the use of tactics can save travel time and increase the number of direct transfers. In this state, a holding strategy or changes in speed can improve service reliability.

**State 3:** *On schedule:* Schedule adherence is shown continuously, and no control strategy for this state is required. To maximize the number of simultaneous arrivals of PT vehicles at transfer points, planning tools involving maximal synchronized timetable (MST) were introduced (Ceder and Tal, 2001, Domschke, 1989). Synchronized PT transfers are used to increase PT network connectivity, reduce passenger-transfer waiting times and improve PT service reliability.

**State 4:** *Behind schedule:* If vehicles drive behind schedule, the in-vehicle passenger travel time will increase, which may result in missed transfers, one of the undesirable features of PT service. Like "ahead of schedule", when vehicles move into this type of unstable system, they invariably become irregular and finally lead to bunching. If it is not too late, some control actions can be used to remedy the service. Skip-stops, short-cut and changes in speed (but not above the legal speed limit) are tactics that can be implemented to decrease the irregularity of the service and increase the number of direct transfers.

**State 5:** *Being considerably behind schedule:* The results of this research show that if a vehicle is too late, then operational tactics may not prove beneficial as the system might remain unreliable. This irregularity will eventually lead to a bunching phenomenon known to be a major cause of unreliable service. Unreliable service for long delays cannot be compensated by the use of tactics, and passengers will have to wait for the next bus or find alternative solutions.

### 4.3.2 Optimal Tactics

As explained in the previous section, one method of repairing the PT system in the operational phase is to implement tactics and strategies in real-time. Nesheli and Ceder (2014) introduced an optimization method that presents an optimal combination of tactics to reduce the uncertainty of the PT system. Such a method can be used when a PT system is operating in the deterioration mode. Therefore, a library of tactics can be constructed and applied in order to bring about system improvement. The following section provides the formulation of the problem.

#### 4.3.2.1 Notation

**Sets:**

$N$  Set of all stops, in which  $n \in N$

$R$  Set of all routes in which  $r \neq x \in R$

$TF$  Set of all transfer points, in which  $tr \in TF$

**State Variables:**

$Q_r^{max}$  Passenger capacity of vehicle of route  $r$

$l_{n,r}$  Passengers' load of route  $r$  at stop  $n$

$b_{n,r}$  The number of boarding passengers of route  $r$  at stop  $n$

$a_{n,r}$  The number of alighting passengers of route  $r$  at stop  $n$

$p_{n,rx}$  The number of transferring passengers of route  $r$  to route  $x$  at stop  $n$

$d_{n,r}$  Vehicle dwell time of route  $r$  at stop  $n$  (in seconds)

$H_r$  Vehicle headway of route  $r$

$m_r$  Maximum total number of stops of route  $r$

$TP_r$  Transfer stop of route  $r$

$T_r$  Vehicle schedule deviation of route  $r$

$\Omega_{n,r}$  Time penalty function of route  $r$  at stop  $n$

$k_r$  Positional stop for a snapshot on route  $r$

**Decision Variables:**

$HO_{n,r}$  Vehicle holding time of route  $r$  at stop  $n$

$S_{n,r}$  Vehicle skipping stop of route  $r$  at stop  $n$ ; if stop skipped= 1, otherwise= 0

$Y_{n,rx}$  Possible transferring from route  $r$  to route  $x$  at transfer stop  $n$ , pre-tactics; if a possible transfer occurs= 0, otherwise= 1

$Z_{n,rx}$  Possible transferring from route  $r$  to route  $x$  at transfer stop  $n$ , post-tactics; if a possible transfer occurs= 0, otherwise= 1.

#### 4.3.2.2 Assumptions

It is assumed that the vehicles are operated in FIFO manner, with an evenly scheduled headway per route. Route information, including travel times between stops, estimation of passenger arrival rates at each stop and average number of transferring passengers are assumed known and fixed over the period concerned. It is also assumed that passengers onboard a vehicle will be informed of any action at the time of the decision so that they can choose to alight before or after the action. It is to note that for the skip-stop tactic the formulation of optimization minimizes the number of passengers who chose to alight; in most cases tested it is nil. Stops where passengers want to transfer cannot be skipped.

#### 4.3.2.3 Optimization Problem Formulation

The problem is formulated as a mixed-integer programming (MIP). The standard optimization software, ILOG (IBM, 2012), is used to solve optimally the value of each decision variables. We utilized constraint programming (CP) engine to solve the problem efficiently. CP is an efficient approach to solving and optimizing irregular problems, e.g., with nonlinear constraints, for exact mathematical optimization (IBM, 2012).

**(a) Holding**

The effect of holding tactic on the change in total passenger travel time with respect to route  $r$  and stop  $n$  is:

$$\Delta TPTT_{Holding_{n,r}} = HO_{n,r} \left[ l_{n,r} + b_{n,r} - a_{n,r} + \sum_{i=n+1}^{m_r} \left( b_{i,r} + \sum_{x \in R, x \neq r} (1 - Z_{i,xr}) p_{i,xr} \right) + \sum_{x \in R, x \neq r} ((1 - Y_{n,xr}) p_{n,xr} - p_{n,rx}) \right] \quad (4.1)$$

with the checking constraint:  $l_{n,r} + b_{n,r} - a_{n,r} < Q_r^{max}$  for restricting the number of passengers onboard (capacity-based) once the vehicle departs the stop.

**(b) Skip-Stops**

Skip-stops encompasses both skip-stop and skip-segment tactics. Consequently the effect of the skip-stops tactic on the change of the total travel time for route  $r$  and stop  $n$  is:

$$\Delta TPTT_{Skip-stops_{n,r}} = S_{n,r} \left[ a_{n,r} \Omega_{n,r} + b_{n,r} (H_r - T_r) - d_{n,r} \left( l_{n,r} + \sum_{i=n+1}^{m_r} \left( b_{i,r} + \sum_{x \in R, x \neq r} (1 - Z_{i,xr}) p_{i,xr} \right) \right) \right] \quad (4.2)$$

where  $\Omega_{n,r}$ , defines the penalty function to take into account the drawback of the skip-stops tactic to the passengers' disadvantaged. That is, the penalty function is determined by the additional walking or waiting times incurred because of the skipped stops.

**(c) Transfers**

It is possible to measure the effect of making or missing synchronized transfers on the change in total passenger travel time by the definition of direct transfers. Therefore, a direct transfer occurs if the following holds:

$$Y_{n,rx} + Y_{n,xr} = 0 \quad (4.3)$$

$$Z_{n,rx} + Z_{n,xr} = 0 \quad (4.4)$$

The binary variables  $Y$  and  $Z$  are used to determine whether or not a direct transfer is made before and after implementation of tactics, respectively. The term "direct



transfer" means a synchronized transfer of vehicles of routes  $r$  and  $x$  without a wait. The real-time transfer problem is formulated as follows:

$$\Delta TPTT_{Transfer_{n,r}} = \sum_{x \in R} [p_{n,rx}(Z_{n,rx} - Y_{n,rx})(H_x - T_r)] \quad (4.5)$$

**(d) Objective Function**

The objective function of the proposed model can be written as:

$$\min \sum_{n \in N} \sum_{r \in R} [\Delta TPTT_{Holding_{n,r}} + \Delta TPTT_{Skip-Stops_{n,r}} + \Delta TPTT_{Transfers_{n,r}}] \quad (4.6)$$

**(e) Constraints**

$$S_{n,r} \left[ \sum_{x \in R} (p_{n,rx} + p_{n,xr}) \right] = 0 \quad (4.7)$$

$$HO_{n,r} = 0 \quad \text{if } (n < k_r) \quad (4.8)$$

$$S_{n,r} = 0 \quad \text{if } (n < k_r) \quad (4.9)$$

$$S_{1,r} = 0 \quad (4.10)$$

$$HO_{n,r} \leq M(1 - S_{n,r}) \quad , \text{ and } HO_{n,r} \geq 0 \quad (4.11)$$

$$HO_{n,r} \leq (1/2)H_r \quad (4.12)$$

$$Z_{n,rx} \leq Y_{n,rx} \quad (4.13)$$

$$\sum_{i=TP_{tr-1,r}}^{TP_{tr,r}} S_{i,r} \leq M \sum_{tr \in TF} Y_{tr,rx} \quad \forall (TP_{tr,r} > TP_{tr-1,r} > k_r) \quad (4.14)$$

$$\sum_{i=k_r}^{TP_{tr,r}} S_{i,r} \leq M \sum_{tr \in TF} Y_{tr,rx} \quad \forall (TP_{tr,r} > k_r > TP_{tr-1,r}) \quad (4.15)$$

$$\sum_{i=k_r}^{TP_{1,r}} S_{i,r} \leq M \times Y_{1,rx} \quad \forall (TP_{1,r} > k_r) \quad (4.16)$$

$$\sum_{i=TP_{tr-1,r}}^{TP_{tr,r}} S_{i,r} \leq M \left( Im - \sum_{tr \in TF} Z_{tr,rx} \right) \quad \forall (TP_{tr,r} > TP_{tr-1,r} > k_r) \quad (4.17)$$

$$\sum_{i=k_r}^{TP_{tr,r}} S_{i,r} \leq M \left( Im - \sum_{tr \in TF} Z_{tr,rx} \right) \quad \forall (TP_{tr,r} > k_r > TP_{tr-1,r}) \quad (4.18)$$

$$\sum_{i=k_r}^{TP_{1,r}} S_{i,r} \leq M \left( 1 - Z_{1,rx} \right) \quad \forall (TP_{1,r} > k_r) \quad (4.19)$$

Constraint 4.7 guarantees that the transfer points cannot be skipped. Constraints 4.8 and 4.9 express that tactics can't be applied on stops that a vehicle is not going to or are already passed. Constraint 4.10 ensures that it is not allowed to skip the first stop. Constraints 4.11 and shows that no skipping and holding at the same stop are allowed; with  $M$  being a large number. Constraint 4.12 states the maximum holding time is not more than half the headway of the route. Constraint 4.13 defines that if a transfer occurs at pre-tactics situation the same apply to with-tactics situation. Constraints 4.14, 4.15, and 4.16 describe that if direct transferring is possible without the use of any tactic, there is no need to interfere, with  $M$  being a large number. Constraints 4.17, 4.18, and 4.19 express that if the use of tactics does not result in a transfer, no tactics are applied, with  $M$  being a large number and  $Im$  stands for the size of  $Z_{tr,rx}$ .

### 4.3.3 Agent-based Modelling

Computation of the system-performance measures requires constructing a simulation model with a proper database. The model can be developed with the creation of an agent-based simulation (ABS) for a PT network of routes, operational transit information, and inter-modal shortest-path calculation, all of which are to be combined with the computation of the performance-indicator measures. ABS is a modern approach in transport modelling. To show the transfer event one or more legs can be defined between origin-destination. In fact, the number of legs describes which transportation modes are used to arrive at the destination. For a bus system, the number of legs minus one expresses how many transfer points are used to go from one (starting) point to another.

The following section provides more information on the system's characteristics and on the use of real-time PT control concept.

## 4.4 System Performance Indicator Model

In order to construct a system performance-indicator (SPI) model it is required to investigate precisely the process of system deterioration. Following are system definitions and properties for deterioration and improvement patterns prior to the description of the SPI model.

### 4.4.1 System Definition and Properties

Consider a system having  $n$  components and  $M$  states. Let  $x_i(t)$  denote a particular component state (e.g., the state of failure relative to a performance criterion) at time  $t$ ;  $x_i(t) \in [1, 2, \dots, m_i]$ ,  $i = 1, \dots, n$  denote vectors of the component states, such that  $m_i$  = the event in which component  $i$  is found in its  $m^{th}$  state. If the structure function of the system is denoted by  $f(x, t)$ , the status of the efficiency of this system at some specified time  $t$  is given by  $f(x, t) = \mu$ , where  $\mu \in [1, 2, \dots, M]$ . The relationship between the components and the system at time  $t$  can then be expressed as follows:

$$f(x, t) : S \rightarrow s \quad (4.20)$$

where  $S = [1, 2, \dots, M]$  is the set of all possible states of the system; and  $s$  is the components' state space, which is the set of all their possible states.

Generally speaking, any state of the working efficiency of a system can be written as follows:

$$S_\mu = \{x | f(x) = \mu\}, \quad \forall \mu \in (1, 2, \dots, M) \quad (4.21)$$

Therefore, all combinations of component states when the system is in the state of  $\mu$  may be described as:

$$S_{system} = \bigcup_{\mu=1}^M S_\mu \quad (4.22)$$

#### 4.4.1.1 State Description

The range of each state can be decided by reliability engineering, based on the condition of the system and the user's preferences (Misra, 2008). Let  $\vartheta$  be the substitute characteristic for the status of the component, and  $\vartheta_1$  the best value or ideal for  $\vartheta$ . Therefore, the state of the component can be expressed as:

$$\left\{ \begin{array}{ll} 1 & \text{if } \vartheta_1 \leq \vartheta \leq \vartheta_2 \\ 1 & \text{if } \vartheta_2 \leq \vartheta \leq \vartheta_3 \\ \vdots & \vdots \\ M & \text{if } \vartheta \geq \vartheta_M. \end{array} \right. \quad (4.23)$$

Figure 4.1 shows the range of states that can define the boundary for the system. The function of the system can be evaluated from the definition of the boundary.

#### 4.4.1.2 System Reliability Deterioration and Improvement Pattern

A system operating for some time gradually deteriorates and functions at intermediate states between performing perfectly and total failure (Boedigheimer et al., 1994). The

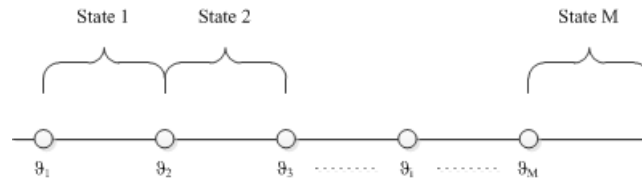


Figure 4.1: States description.

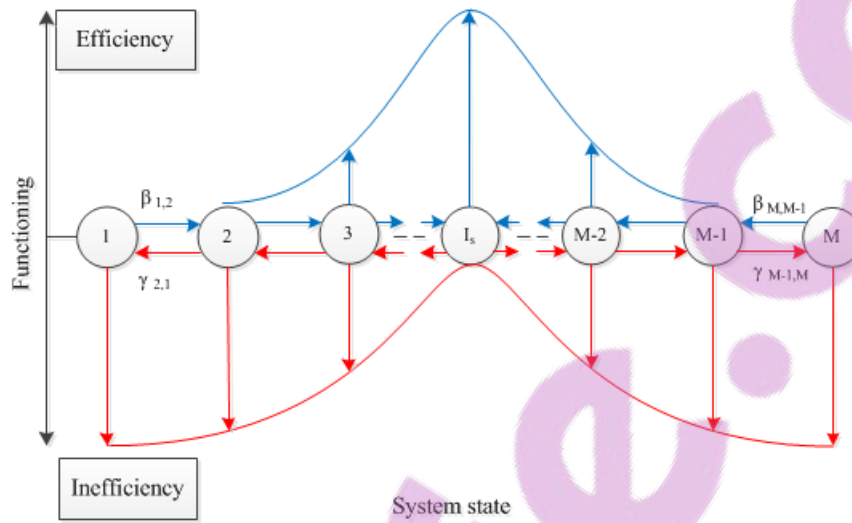


Figure 4.2: System deterioration and repair.

deterioration process can be modelled using multiple states of operation for  $M$  different states. Let  $I_s$  be the ideal state of the system, in which a system is functioning perfectly. Consequently,  $F(x)$ , the function of the system at time  $t$ , could be at differing levels of working efficiency. The value of  $F(x)$ , therefore, defines the measure of reliability and can be used to assess the system at a particular time. In order to maintain the system at an acceptable level of functionality, an intervention method can be used. This acceptable level is between the failure and perfect states of operation. An intervention method deals with a repair rate for the recovery of a system. To illustrate a comprehensive process a system deterioration rate  $\gamma_{(i,j)}$  can be defined, where  $i, j \in [1, 2, \dots, M]$  represents the states of the system. In contrast,  $\beta_{(i,j)}$  represents the recovery of the system between states  $i$  and  $j$ . Figure 4.2 depicts such a system status. Certain tactics and strategies can be used to determine the acceptable level of system reliability to the user's satisfaction. Figure 4.2 shows that when the state of the efficiency is on the low curve, the red zone, the system is functioning with poor efficiency. Conversely, when the system is working at higher efficiency, the "its state" stands on the top curve, the blue zone. In addition, the figure illustrates when the system should be repaired, blue curve suggesting how much of

**Table 4.1:** State of vehicle with possible tactics

State	Possible Tactics and Strategies	$\alpha$
1	No control applicable	+1.5
2	Holding, change speed	+1
3	Regular service—do nothing	0
4	Skip-stop, short-cut, change speed (not above the legal speed limit)	−1
5	No control applicable	−1.5

the recovery method is effective to move the system to an ideal state.

Once system's deterioration pattern is detected it is useful to define user's satisfaction, over time, with the system's recovery process. In order to measure the user's total experience with the system, utility or disutility function can be used. If  $U(F(x))$  is the disutility function of the system for all conditions (with or without interventions), it is then possible to compute the expected total disutility of the user's experience with the system during a specific period of time.

#### 4.4.2 System Performance-indicator (SPI) Model

Quality of service is an essential consideration for making a decision about any intervention (Misra, 2008). The service quality can reasonably be assumed to change with the state of vehicles and the type of tactics received. To evaluate the effect of each tactic on the system, a disutility function is defined. The disutility function can be used as a measurement of user satisfaction (Misra, 2008). The total disutility function can be defined, then, as the sum of the related state disutilities with an additional term of a state specific constant  $\alpha$ . Table 4.1, describes the parameter of  $\alpha$  for different situation types (states) and possible tactics. It should be noted that a plus sign indicates that the bus is running ahead of schedule, and a minus sign that it is running behind schedule. The schedule-adherence measure is given as zero.

Let  $\alpha$  be the bus-situation index ( $|\alpha| = 1$  for a schedule deviation that can be compensated for with the optimal suggested tactic). Also, let  $\delta$ , a non-negative integer, be the leg-number index that describes any trip changes between origin-destination. For example, when  $\delta = 1$ , this means that a passenger has a single-legged trip with no transferring;

for  $\delta > 1$ , however, the passenger should have at least one transfer. The following system-performance indicators (SPI) may then be constructed:

$$SPI_{i,j,k} = \Gamma_{i,j,k} \sum_{\delta} U_{total}(S_{r_{i,j,k,\delta}}, [|\alpha| + u_F] \cdot H_{r_{i,j,k,\delta+1}}) \quad (4.24)$$

$$SPI = \sum_i \sum_j \sum_k SPI_{i,j,k} \quad (4.25)$$

where  $\Gamma_{i,j,k} = \frac{TPTT_{i,j,k}}{TPTT_{system}}$  and  $TPTT_{i,j,k}$  is the total travel time for passengers on trip  $k$  when traveling between origin  $i$  and destination  $j$ . Let  $S_{r_{i,j,k,\delta}}$  denote a particular system state of interest (e.g., the vehicle situation state relative to a prescribed performance criterion). The disutility function of each trip can be achieved by the definition of different functions. For the disutility function of  $u_F$ , the following function can be considered:

$$u_F = \bigcup_{f=1}^n u_f \quad \forall f \in (1, 2, \dots, n) \quad (4.26)$$

For this study,  $u_F$  is defined according to the three following components:

- (i).  $u_1$  = Passengers' extra time from implementing the suggested tactics with reference to scheduled travel time.
- (ii).  $u_2$  = Passengers' saving time from implementing the suggested tactics with reference to scheduled travel time.
- (iii).  $u_3$  = Passengers' transferring time (if direct transferring occurred, it is considered zero).

Finally, computing the total disutility function for any system event is possible; where  $U_{total}(S_{r_{i,j,k,\delta}}, [|\alpha| + u_F] \cdot H_{r_{i,j,k,\delta+1}}) =$  disutility function, with state and headway as parameters.

The SPI aims at measuring the level of service; as a performance indicator, it takes into account the use of tactics weighted by passenger travel time and the headway. The rationale behind the performance indicator stems from the fact that the headway has a major impact on the level of service and at the same time is comparably easier to change. Hence, the higher the SPI value, the lower is the performance of the PT system, with  $SPI = 0$  represents a perfect system performance.

**Table 4.2:** Disutility function for related tactic

Tactic	$u_1$	$u_2$	$u_3$
Skip-Stops	Extra time for passengers that wanted to alight and those wanted to board	Saves dwell time, increases the direct transferring	The encounter probability, if the passengers miss the direct transfer they will tolerate extra time for transferring
Holding	Increases the in vehicle travel time	Reduces headway variation , maintains the schedule and increases the direct transferring	

The performance of the system is evaluated according to metrics representing system reliability and efficiency. System reliability is represented by schedule deviation, which is calculated across all bus trips at the reference stops. A lower schedule deviation results in lower passenger waiting times, indicating greater system reliability. System efficiency is represented by the effect of using different tactics on passengers per bus trip for different events. Although the library of tactics can be employed to improve on-time performance (scheduled-based), eliminating bunching (headway-based) and responding to unexpected demand (entire system), it has an adverse effect on some passengers. For example, a longer holding time leads to a longer bus trip for on-board passengers, and thus higher passenger travel times. A lower schedule variance and shorter holding times indicate better control performance. A summary of the attributes of the disutility function for a related tactic is presented in the Table 4.2.

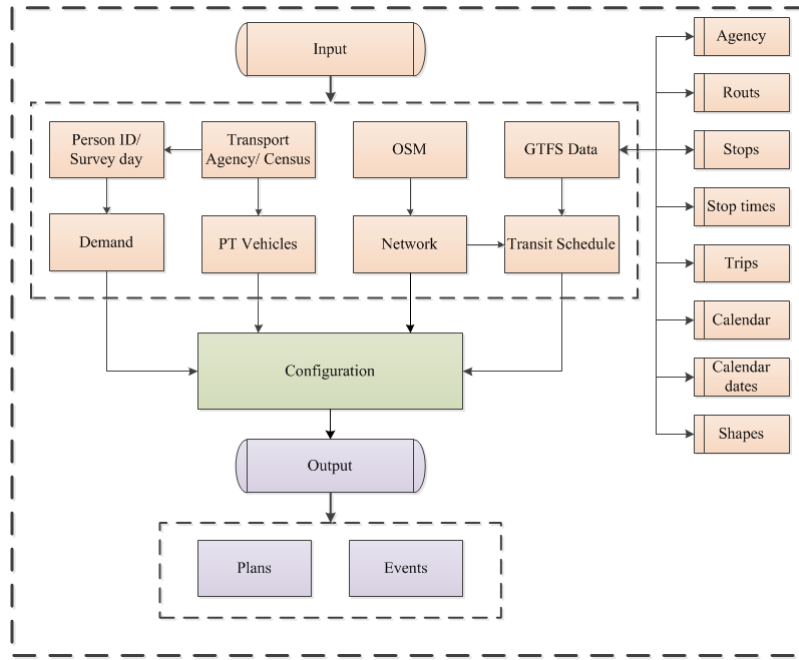
## 4.5 Analysis of the Methodology

### 4.5.1 Simulation Environment

In order to analyze the performance-indicator method presented, an agent-based simulation method was developed. Multi-Agent Transport Simulations (MATSim) (Multi-Agent Transportation Simulation, 2014), provides a framework for implementing agent-based simulations. For a simulation of the PT system in MATSim, the following data is required:

- (i). *Configuration file*: Specifying the parameters of the simulation.

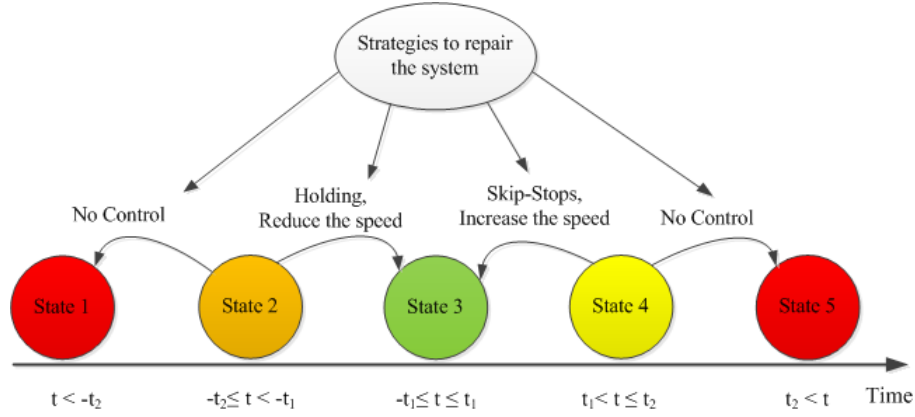




**Figure 4.3:** An agent-based simulation modelling framework.

- (ii). *Multimodal network:* A network of links and nodes representing the road and infrastructure of the area.
- (iii). *Population:* A synthetic population of agents, each with attributes and a plan; for this study APC data was used.
- (iv). *Transit schedule:* The transit schedules of the entire network, with stop locations, departure times and routes specified.
- (v). *Transit vehicles file:* A description of every type of transit vehicles operating in the PT system, including vehicle specifications, speed, capacity and length.

The model uses three sources of information: 1) General Transit Feed Specifications (GTFS) as a source for a public-transit schedule; 2) Open Street Map (OSM) data as a source of network attributes; and 3) local-transport agency as a source for demand and fleet size. Figure 4.3 illustrates the general structure of the simulation model.



**Figure 4.4:** Time-State diagram at the control stop, with next-stop strategies up to the transfer point.

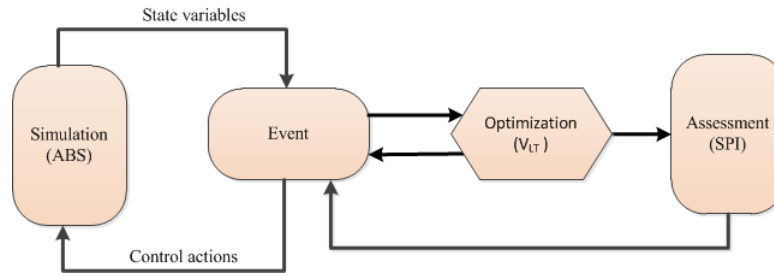
## 4.5.2 Simulation Analysis

### 4.5.2.1 Events and States

To complete the simulation and address the state of a bus at different situation, an event was outlined as were the control strategies to repair the uncertainty problem. Figure 4.4 illustrates a range of different event determined by the simulation runs. These events feature the control strategies (selected operational tactics) described in Section 4.4. For all events, different states can be defined to describe the possible status of a vehicle at control stops. In MATSim, events are used to document changes in the state of an object. When the event occurred, information of the time of the event, the "id" of the agent who caused the event or the id of the link where the event happened could be included. Figure 4.4 also demonstrates the boundary of each state; it shows when the range of each state changes. This range can be determined by the optimization model. It should be noted that time is schedule time (i.e. when a bus reaches  $(-2)$ , it means 2 minutes ahead of schedule;  $t = 0$  means schedule adherence). A vehicle in State 2 or 4 can be in State 3 straight after receiving the related intervention (tactics).

### 4.5.2.2 Travel Time

The travel time attribute for PT consists of running time, dwell time and waiting time. Running time is based on the published transit timetables. Assuming that the timetables are realistic, the travel time between two adjacent stops is estimated by



**Figure 4.5:** General analysis framework.

averaging the difference between departure and arrival times at the two stops within a specific time window. In the dwelling process, boarding and alighting take place at different doors. Boarding and alighting times per passenger were set at 2.5 and 1.5 seconds, respectively. The total dwell time is then estimated as the maximum time between these two processes. For short headways passengers arrive randomly following a Poisson distribution at each stop. This distribution is commonly used in PT services with headways of less than 12min (Jolliffe and Hutchinson, 1975, Okrent, 1974). For longer headways, passengers tend to consult the schedules to avoid unnecessary waiting time. The boarding process follows a FIFO discipline.

### 4.5.3 Framework of Analysis

To implement the suggested tactics, the first step of simulation run was recorded on the event file without any tactics. The evaluation of this step included the number of direct transfers and deviations from the bus schedule at different locations. Consequently, the suggested tactics can be applied to compensate for schedule deviations. The information on the buses in each state provided input for the optimization model (as part of the second step). Based on the optimization output, the boundary of each state and the value of suggested tactics ( $V_{LT}$ ) are determined. The  $V_{LT}$  denotes the optimal value of a tactic for each event. This optimal solution will naturally tend to maximize the number of direct transfers and the potential saving of total passenger travel time. Lastly, the level of system efficiency, based on the utilized tactics, is quantified. Figure 4.5 illustrates the general analysis framework.

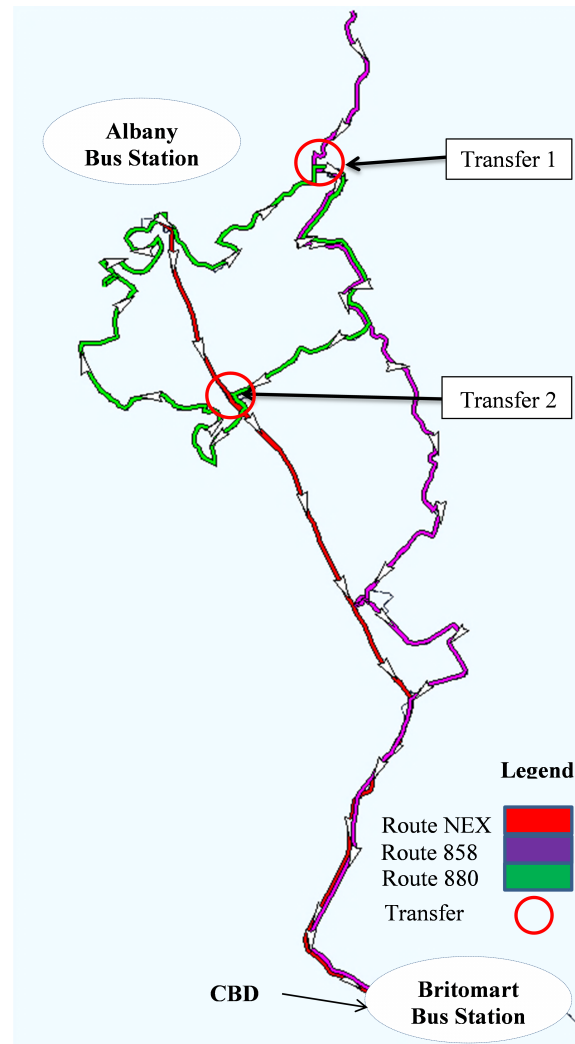
## 4.6 Case Study

The analysis carried out was based on a case study of Auckland, New Zealand, the country's largest and busiest city, whose PT system has been criticized as not being efficient (Mees, 2010). More recently, the Auckland Transport Regional Public Transport Plan (AT, 2013) was created for the purpose of developing an integrated transport network to provide Aucklanders with a sustainable transport system in a safe, integrated and affordable manner. This plan shows the intensive discussion conducted about various issues relating to PT systems of the future; indeed, a major focus over the next decade will be on enhancing the PT system. Thus, there is need to investigate the performance of Auckland's PT system. A case study for the Auckland region was conducted, based on AT (Auckland Transport) data, which consisted of the PT network, AT- HOP cards (Auckland Integrated Fares System), OD pairs and a PT demand data. The data for each stop contain bus ID, arrival and departure times, number of boarding and alighting passengers, and the number of passengers onboard the bus upon departure. In addition, the scheduled departure times are known. Passenger data was collected for 4 weeks on March 2014 by ITS system (AT-HOP card). That is, the time and location of boarding and alighting of passengers are provided. Average headways and dispatch times are assumed to be known at both Transfer Point 1 and Transfer Point 2. In addition, vehicle capacity was given as 60 passengers, with 40 seats and 20 standings.

The PT network data is based on AT transit feed dated May16, 2014. Analysis was carried out on three bus routes and two transfer points. The first route, known as Northern Express (NEX), has a dedicated lane that runs from the suburbs across the Auckland CBD area; it transports quite a high number of passengers during peak hours. The second route, Route 858, runs north-south (east of the first route); and the third route, Route 880, is a loop that serves as a feeder route. Figure 4.6 illustrates the three routes and the two transfer points.

## 4.7 Results

The performance indicator was evaluated with the total passenger travel time. The events were extracted from the simulation model for 24 hours. Based on the optimization process, the maximum hold time observed in all events was 106 seconds, subject to



**Figure 4.6:** Bus system and the study routes, Auckland, New Zealand.

the length of headways; the average hold time was 30 seconds. The maximum number of skipped stops is 6 for a vehicle trip. For each trip, the states of the bus situation with reference to different events were computed, along with the disutility function and SPI. Table 4.3, summarizes the results for ten events tested to evaluate the reliability and efficiency of the system under different operational conditions. Table 4.3 describes the main results of the performance indicators.

Table 4.3: Results of performance indicators

OD	Trip	$\Gamma$ (%)		Event(sec)		$\alpha$		H(min)	$u_1\%$	$u_2\%$	$u_3\%$	SPI
1-1	R1	T1	T2	T1	T2	T1	T2					
		0.24	-158	-281	-1.5	-1.5	10	0	0	0	0	7.20
		0.24	-120	-252	-1	-1.5	10	0.07	-0.12	-0.12	0	5.88
		0.24	-95	-185	-1	-1.5	10	0.06	-0.11	-0.11	0	5.88
		0.24	-49	-142	-1	-1	10	0.05	-0.13	-0.13	0	4.61
		0.24	-21	-91	0	-1	10	0.05	-0.12	-0.12	0	2.23
		0.24	19	-41	0	-1	10	0.04	-0.09	-0.09	0	2.28
		0.24	41	16	1	0	10	0.01	-0.09	-0.09	0	2.21
		0.24	97	21	1	0	10	0.02	-0.1	-0.1	0	2.21
		0.24	120	54	1	1	10	0.02	-0.09	-0.09	0	4.63
		0.24	41	16	1	0	10	0.01	-0.09	-0.09	0	2.21
1-2	R1-R2											
		0.03	-158		-1.5		20	0	0	0	0.21	1.03
		0.03	-120		-1		20	0	-0.25	-0.25	0	0.45
		0.03	-95		-1		20	0	-0.39	-0.39	0	0.37
		0.03	-49		-1		20	0	-0.32	-0.32	0	0.41

	0.03	-21	0	20	0	0	0	0.00
	0.03	19	0	20	0	0	0	0.00
	0.03	41	1	20	0	-0.44	0	0.34
	0.03	97	1	20	0	-0.39	0	0.37
	0.03	120	1	20	0	-0.21	0	0.47
	0.03	192	1.5	20	0	0	0.19	1.01
1-3	R1-R3							
	0.02	-281	-1.5	15	0	0	0.24	0.52
	0.02	-252	-1.5	15	0	0	0.25	0.53
	0.02	-185	-1.5	15	0	0	0.33	0.55
	0.02	-142	-1	15	0	-0.34	0	0.20
	0.02	-91	-1	15	0	-0.28	0	0.22
	0.02	-41	-1	15	0	-0.33		0.20
	0.02	16	0	15		0	0	0.00
	0.02	21	0	15		0	0	0.00
	0.02	54	1	15	0	-0.47	0	0.16
	0.02	89	1	15	0	-0.26	0	0.22
2-2	R2							
	0.39	-192	-1.5	20	0	0	0	11.70

	0.39	-112	-1	20	0.05	-0.11	0	7.33
	0.39	-90	-1	20	0.04	-0.09	0	7.41
	0.39	-63	-1	20	0.04	-0.08	0	7.49
	0.39	-26	0	20	0	0	0	0.00
	0.39	25	0	20	0	0	0	0.00
	0.39	45	1	20	0.01	-0.1	0	7.10
	0.39	98	1	20	0.01	-0.08	0	7.25
	0.39	110	1	20	0.02	-0.07	0	7.41
	0.39	141	1	20	0.01	0.06	0	7.41
2-1								
R2-R1								
	0.07	-192	-1.5	10	0	0	0.29	1.25
	0.07	-112	-1	10	0	-0.37	0	0.44
	0.07	-90	-1	10	0	-0.35	0	0.46
	0.07	-63	-1	10	0	-0.28	0	0.50
	0.07	-26	0	10	0	0	0	0.00
	0.07	25	0	10	0	0	0	0.00
	0.07	45	1	10	0	-0.42	0	0.41
	0.07	98	1	10	0	-0.37	0	0.44
	0.07	110	1	10	0	-0.39	0	0.43



2-3	R2-R1-R3	0.07	141	1	10	0	0.26	0	0.52
2-3	R2-R1-R3	0.01	-192	-1.5	-1.5	0	0.47	0	0.47
		0.01	-112	-1	-1.5	0	0.36	0	0.41
		0.01	-90	-1	-1.5	0	0.36	0	0.36
		0.01	-63	-1	-1	0	0.18	-0.31	0
		0.01	-26	-1	-1	0	0.20	-0.22	0
		0.01	25	0	-1	0	0.11	-0.3	0
		0.01	45	1	0	0	0.05	0	0
		0.01	98	1	0	0	0.05	0	0
		0.01	110	1	1	0	0.18	-0.34	0
		0.01	141	1	1	0	0.21	-0.16	0
3-3	R3	0.22	-120	-1.5	-1.5	0	0	0	4.95
3-3	R3	0.22	-88	-1	15	0.04	-0.13	0	3.00
		0.22	-50	-1	15	0.04	-0.15	0	2.94
		0.22	-21	0	15	0	0	0	0.00
		0.22	19	0	15	0	0	0	0.00
		0.22	42	1	15	0.02	-0.14	0	2.90

	0.22	86	1	15	0.01	-0.11	0	2.97
	0.22	110	1	15	0.02	-0.11	0	3.00
	0.22	132	1	15	0.02	-0.09	0	3.07
	0.22	185	1.5	15	0.03	0	0	4.95
3-1	R3-R1							
	0.02	-120	-1.5	10	0	0	0.31	0.36
	0.02	-88	-1	10	0	-0.28	0	0.14
	0.02	-50	-1	10	0	-0.24	0	0.15
	0.02	-21	0	10	0	0	0	0.00
	0.02	19	0	10	0	0	0	0.00
	0.02	42	1	10	0	-0.37	0	0.13
	0.02	86	1	10	0	-0.31	0	0.14
	0.02	110	1	10	0	-0.21	0	0.16
	0.02	132	1	10	0	-0.18	0	0.16
	0.02	185	1.5	10	0	0	0.24	0.35

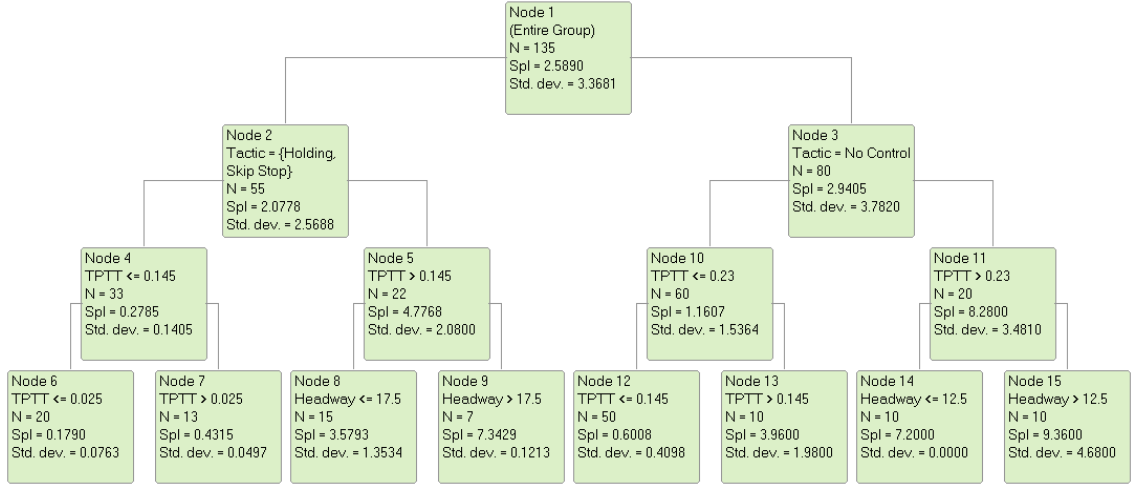
T= Transfer point; H= Headway; R1= Route 880, R2= Route 858, R3= NEX

From the results of Table 4.3 it is possible to draw an immediate conclusion about the library of selected tactics used to improve the overall system performance. The results demonstrate that the SPI index of no control policy is 274.80 as compared with SPI of 114.60 when using operational tactics; this is a reduction of 58% across the system. For a schedule deviation of between  $\pm 26$  seconds, direct transfer occurs without the implementation of any tactic, and the SPI is zero (a perfect case). Generally speaking, the results also show a somewhat superior outcome for State 2 using holding tactic than for State 4 using skip-stops. It is to note that each color coding, stands for a change in one state. For example the red zone indicates State 1 or 5 (large schedule deviation), where no control action is applicable. Likewise, the green and orange colors show the results for those events that are behind (State 4) and ahead (State 2) of the schedules, respectively. Consequently, each state is compensated by means of related operational tactics.

#### 4.7.1 Sensitivity Analysis

In order to understand the importance of each independent variable for computing the SPI, a decision tree (DT)-based method was used. DT-based methods can automatically detect interaction between independent variables through the tree structure. The applicability, efficiency and other strengths of DT-based methods have been proven in transportation engineering (Abdel-Aty et al., 2005, Karlaftis and Golias, 2002). In this study, a novel sensitivity analysis method, called classification and regression trees (CART), which as the name implies is a DT-based method, was applied to assess the use of different input variables on the SPI.

As expected, the CART algorithm categorized SPI into several homogenous groups. Figure 4.7 shows that the tree is constructed on the basis of two strategies "Tactics" and "No Control", total passenger travel time, "TPTT" and "Headway". The first CART box, known as root node, depicts the total data (N), the mean and the standard deviation of the SPI. The next branch splits to demonstrate two intermediate nodes: "Tactics" and "No Control". In the "Tactic" box, "TPTT" is considered the most important factor to compute the SPI. It may also be observed that by increasing "TPTT", the longer headway has a higher SPI value. This indicates that applying the tactic of a short headway attains a considerable reduction of SPI. In addition, the results exhibit that with "No Control" of the system, the longer headway has a higher SPI value, in which "TPTT" increases.



**Figure 4.7:** Effect of "No-Control" vs. "Holding-Skip-Stops" strategy on SPI.

Figure 4.8 demonstrates the effect of each tactic on the system. That is, "TPTT" is the only important factor for the "Holding" tactic. As expected, the higher "TPTT" in this case leads to a higher SPI value. For the "Skip-Stop" tactic, besides the "TPTT", headway is also an important factor. With this tactic, the longer headway results in a higher SPI value when "TPTT" increases. This shows that implementing a skip-stop tactic for a long headway requires more attention. For example, if passengers cannot board, they will experience longer waiting times. This also indicates that the marginal burden or disutility of out-of-vehicle waiting time is perceived to be significantly more burdensome than in-vehicle travel time; different studies have argued this issue (Reed, 1995). Hence, for developing any skip-stop model, more weight should be given to the penalty function of skipping stops.

#### 4.7.2 Computational Times

The mathematical formulation was coded in OPL using ILOG and implemented on an Intel Core<sup>TM</sup> i5 – 2500 CPU @ 3.30 GHZ and 8.00 GB RAM. The execution time of the procedure varies between 5-11 seconds for a proposed PT system model with 133 stops of the Auckland's case study. This short time range allows for using the proposed model in a real-time scenario.

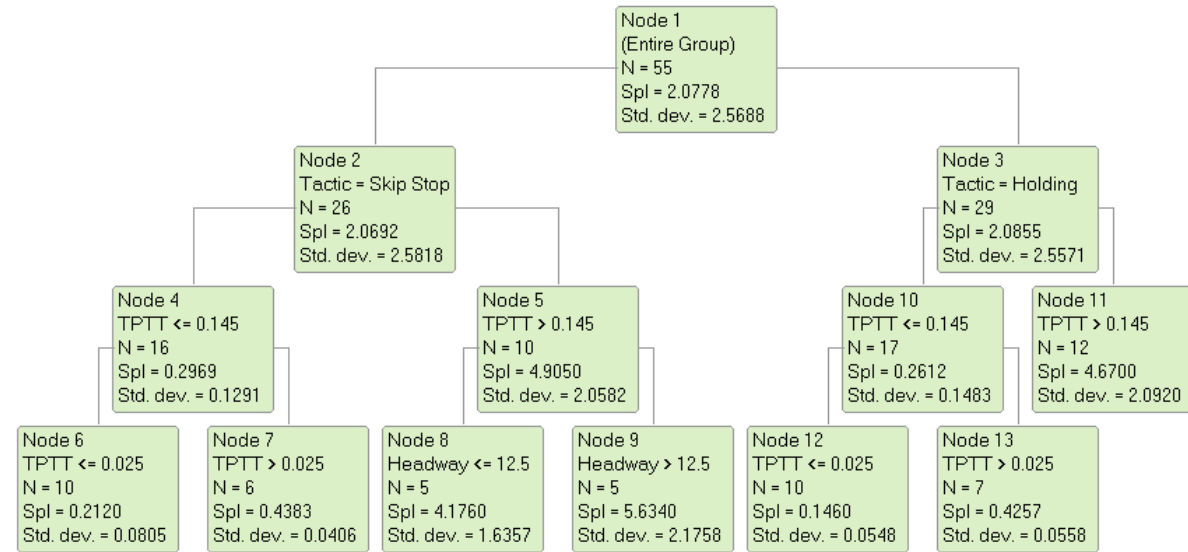


Figure 4.8: Effect of "Holding" vs. "Skip-Stops" tactic on SPI.

## 4.8 Concluding Remarks

In order to implement strategic measures that will effectively encourage the use of routes with transfers, it is essential to develop operational tactics and strategies for minimizing passenger waiting time at transfer points and for approaching the ideal of direct transfers without waiting. This will undoubtedly make the PT service more attractive. In this study, besides the reliability of the PT system, the effect of each tactic on system performance was also investigated. System reliability is represented by schedule deviation, which was calculated across all bus trips at the control stops. Lower schedule deviation results in lower passenger waiting times and indicates greater system reliability. System efficiency is represented by the effect of using different tactics on each bus trip for different events. The results produced by this study are important for the real-time operation of any PT system. Generally speaking, this study prepares the ground for practitioners to deliver not only the optimal operational tactics, but also practical ranges of suggested tactics based on categorized states. The most important outcome, which is proved by the case study presented, is that the system's performance was enhanced by up to 58% with the aid of a proper combination of tactics in the right state at the right time. Moreover, the analysis shows that the skip-stop tactic is sensitive to headway and total passenger travel time. Thus, operators should pay attention to this fact when they consider using such a

tactic, especially for long headways and with higher total passenger travel time.

The analysis also indicates significantly better results for the holding tactic when the total passenger travel time is low. This study makes five important contributions: 1) it introduces a simplified analysis for measuring public transport system performance; 2) it proposes a public transport system deterioration and repair model; 3) it develops an agent-based simulation model; 4) it enables a new method for sensitivity analysis of total passenger travel time, different strategies, and headways and their effect on the system; and 5) it makes it possible to simulate what-if scenarios, such as change of demand because of unexpected passenger overflow, different combination of operational tactics and minor changes in the transit network in real-time.

It is to note that this study utilizes a different perspective and modeling of optimal combination of PT operational tactics than Nesheli and Ceder (2014). Further studies can examine other operational tactics, especially given today's advances in communication technologies; they can add more functions to the disutility function. Finally, a practical guidebook for PT operators and drivers can and should be developed to improve service reliability.

The next chapter investigates the effect of using the library of tactics on minimizing the bunching phenomenon.



## Chapter 5

# Real-time Public-Transport Operational Tactics Using Synchronized Transfers to Eliminate Vehicle Bunching

*Accepted in:*

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(Nesheli et al., 2015e)

### 5.1 Abstract

Scheduled public transport (PT) service on a defined network often encounters unforeseen variations of arrival times mainly because of traffic problems, unexpected passenger demand and driver's behavior. These variations will create the undesirable vehicle (especially bus) bunching phenomenon unless a proper control action is introduced. This study develops a methodology to attain optimally real-time control actions so as to minimize the bunching phenomenon. To this end, a 'library' of selected operational tactics is constructed, for the PT operators, to assist in reducing not only vehicle bunching, but also to increase the likelihood of direct (without wait) transfers. The library of operational tactics serves as a basis for a process of real-time control actions



to maintain the scheduled headway and thus achieving maximal transfer synchronization. The methodology developed, using simulation, is applied to a case study of actual bus routes operated in the region of Auckland, New Zealand. The results imply what tactic to use in real time, what is the optimal control strength, and what is the saving of riding and waiting times in comparison with PT operation without using tactics. The findings show that a significant improvement, in avoiding bunching and increasing the number of direct transfers, is attained by the use of a combination of selected tactics.

## 5.2 Introduction

Service reliability is one of the key factors to affect public transport (PT) operations from the user and agency perspectives. Unreliable PT service was found to be one of the main reasons to considerably reduce the attractiveness and the good image of the PT service (Ceder, 2007, 2015). Different classes and types of measures are employed at each level of the transit operations planning process to provide integrated, coordinated and seamless PT service (Ceder and Tal, 2001, VoSS, 1992). However, in practice, because of some uncertain and unexpected factors such as traffic disturbances and disruptions, inaccurate PT driver behavior and actions, and random passenger demands, preplanned scheduled PT services do not always occur, especially the synchronized transfer service. The combined effect of these factors on PT operations increases the difficulty in maintaining PT vehicles' headway. The headway irregularity may result in increased passenger waiting time and lead to missed transfers. Missed connections of a transfer service will not only frustrate current passengers, but also cause a loss of potential new users.

### 5.2.1 Literature Review

It is a common phenomenon to observe that a bus falling slightly behind schedule tends to pick up more passengers, causing it to slow down until it eventually bunches with a trailing bus (Barnett, 1974, Newell, 1974). Though the bunching could be eliminated to some extent by slowing the trailing bus, this will lead to increased travel times of the passengers aboard the latter.

Several studies have discussed different advanced control models to produce headways within a given tolerance or preplanned schedules by delaying or increasing the speed

of vehicles. Various holding control models were developed to purposefully delay an en route vehicle that is ahead of schedule (Delgado et al., 2012, Hickman, 2001, Osuna and Newell, 1972, Turnquist and Blume, 1980). The findings indicate that holding control might cause additional delays for onboard passengers and increase vehicle travel times. Cats et al. (2011) presented a dynamic transit simulation model, BusMezzo, to investigate a holding strategy considering the interactions among passenger activity, transit operations and traffic dynamics. Some other methods such as speeding control models were developed to reduce vehicle travel times by increasing operating speeds (e.g. by skipping stations) (Sun and Hickman, 2005). Skip-stop can be implemented to decrease the irregularity of service and increase the number of direct transfers. The advantage of skip-stop is for passengers who already are onboard the bus and those to board downstream. On the other hand, it has an adverse effect on passengers who want to alight or board at the skipped stop (Nesheli and Ceder, 2014).

Strategies to increase the efficiency of a high frequency PT route were studied by Daganzo who showed that without interventions, bus bunching was almost inevitable regardless of the driver's or the passengers' behavior (Daganzo, 2009). An adaptive control scheme was analyzed to mitigate the problem. The suggested model dynamically determines bus holding times at route control points based on real-time headway information. The recent study by Ji and Zhang (2013) also proposed a robust dynamic control strategy to regulate bus headways and to prevent buses from bunching by holding them at bus stops. They developed a controlling method to produce better system reliability than that of some existing control strategies.

Controlling methods using operational tactics to alleviate the uncertainty of simultaneous arrivals was demonstrated by Hadas and Ceder (2010a). Previous studies by Liu et al. (2014) and Nesheli and Ceder (2014) also showed that by using some selected operational tactics, the frequency of direct-transfers can be significantly improved and the total passenger travel time can be reduced.

To date there are some real-time PT system control problems, not yet addressed, about using, in practice, operational tactics. The following were found to be the main problems.

- (i). In previous studies the effect of only one or two operational tactics is examined where, in fact, a combination of operational tactics can be used.

- (ii). The PT network structure of previous studies was not complex. It includes only one route or a small unidirectional network with the link's travel time assumed to be deterministic, thus not so realistic.
- (iii). The investigation of the performance in previous studies did not consider long PT routes serving high passenger demand.

This study, unlike others, uses the availability of real-time information to quickly correct headway irregularity and allows for increasing the chances of simultaneous transfers. With the availability of real-time automatic vehicle location (AVL), vehicle speed, the number of passengers, the number of transferring passengers, and vehicle departure and arrival time information, operational tactics can be used online and in real time. This can make the use of some operational tactics more practical and effective in a dynamic traffic environment, and contribute to further improving the number of direct transfers. An event-activity based, transport-simulation framework is also developed to represent a real-life example to evaluate the proposed theoretical model. Based on the proposed framework, both the uncertainty of the PT service and total passenger waiting times are reduced by increasing the number of direct transfers.

## 5.3 Control Methodology

### 5.3.1 System Description

The system underlying the model consists of main and feeder routes. The transfers occur at separate transfer points for each route. The service area includes  $n = 1, 2, \dots, N$  stops and  $r = r, \acute{r}, \dots, R$  routes. A route is made up of a collection of "trips"; each trip  $k$  represents a single vehicle run, based on a certain departure time, along the series of stops on the route.

### 5.3.2 Assumption

1. The vehicles are operated in a FIFO manner, with an evenly scheduled headway per route.



2. Route information, including, travel times between stops, estimation of passenger arrival rates at each stop and average number of transferring passengers, are presumed known and fixed over the period concerned.
3. Passengers onboard a vehicle will be informed of any action at the time of the decision, thus, that they can choose to alight before or after the action.
4. The PT drivers comply with the speed-change and holding instructions provided by their operator.

### 5.3.3 Headway-based Model

In order to alleviate the bunching problem and improving PT service reliability, we propose a dynamic headway-based model according to real-time vehicles motion information instead of schedule-based counterpart. In the analysis conducted in this study, a measure of headway variation is shown continuously. This measure is calculated according to the actual location of the PT vehicle that can be easily known in real-time from GPS and AVL data. A plus sign indicates that the vehicle is running above maximum  $[max]$  headway and a minus sign indicates that the vehicle is running below minimum  $[min]$  headway.

Let  $x_{k,r}$  denotes the position of bus  $k$  on route  $r$  at time  $t$ , and  $s_{k,r} = x_{k-1,r} - x_{k,r}$  is the spacing between vehicles and  $v_{k,n,r}$  is the current vehicle speed observed instantaneously. The displayed measure is estimated with the following formula:

$$h_{k,n,r} = \frac{s_{k,r}}{|v_{k,n,r} - v_{k-1,n,r}|_t}, \quad v_{k,n,r} \neq v_{k-1,n,r} \quad (5.1)$$

where  $h_{k,n,r}$  is the actual headway for the driver on trip  $k$  when driving between consecutive stops of route  $r$  rounded down to the closest divider of time  $t$ . To ensure that headways can be kept close to the ideal everywhere along the route, sufficient control points are used to reduce the need for large corrective actions. This yields the following expressions for headway variations related to earliness ( $E$ ) and tardiness ( $T$ ):

$$E_{k,n,r} = \max[(\min H_{k,r} - h_{k,n,r}), 0] \quad (5.2)$$

$$T_{k,n,r} = \max[(h_{k,n,r} - \max H_{k,r}), 0] \quad (5.3)$$

where  $H_{k,r}$  is the planned headway with its "min" and "max" as the boundary to trigger an intervention (applied tactic). Hence, it is useful to define a state variable,  $\xi_{k,n,r}$ , that is the deviation of the headway for a given vehicle trip  $k$  from the desired headway:

$$\xi_{k,n,r} = \alpha E_{k,n,r} + \beta T_{k,n,r}, \quad 0 \leq \alpha \leq 1, \quad 0 \leq \beta \leq 1 \quad (5.4)$$

The constants  $\alpha$  and  $\beta$  characterize the policy and the sensitivity of control. Overall, to avoid bunching problems and keep the system running on time, the following expression is defined:

$$Z = \sum_k \sum_n \sum_r \xi_{k,n,r} \quad (5.5)$$

The developed model focuses to minimize  $Z$  by implementing proper tactics from a library of tactics on each PT trip for different events. To evaluate the additional travel time per passenger because of unreliable service, the waiting time at the stops should be considered. The expected waiting time for randomly arriving passengers (Ceder, 2007, 2015) with headways of no more than 10 – 12 minutes can be calculated as:

$$W_{k,n,r}^{stop} = \frac{H_{k,r}}{2} \left( 1 + \frac{\sigma^2(h_{k,n,r})}{H_{k,r}^2} \right) \quad (5.6)$$

where

$W_{k,n,r}^{stop}$  = average waiting time at a stop;

$\sigma^2(h_{k,n,r})$  = variance of headway at a stop.

An important reason for the headway irregularity is the variations in passenger demand at that stop. A higher passenger demand at one stop may results in an excessive vehicle dwell time, which contributes to further delays and increases passenger waiting times at downstream stops. In this respect  $\gamma_{n,r}$  is defined a dimensionless measure of the

demand rate at stop  $n$ , equivalent to the ratio between the passenger arrival rate (in passengers/minute) and the total passengers' arrival rate (also in passengers/minute). For most vehicle lines, alighting moves are performed quickly making the increased service delay depends mostly on boarding moves. Thus, the passengers boarding time at stop  $n$  increases by  $\gamma_{n,r}$  if the headway increases by one unit time. Equation 5.6 can be rewritten in the following way:

$$W_{k,n,r}^{stop} = (1 + \gamma_{n,r}) \left[ \frac{H_{k,r}}{2} \left( 1 + \frac{\sigma^2(h_{k,n,r})}{H_{k,r}^2} \right) \right] \quad (5.7)$$

According to Equation 5.7, the waiting time is minimum for a certain average headway if the variance of the headway equals zero. Luethi et al. (2007) found this approximation to be true only for relatively short headways; in the case of longer headways, passengers tend to time their arrivals at the stop to reduce waiting time. It is also shown that passengers travelling during peak hours, such as regular commuters, tend to plan their arrivals, whereas passengers travelling during off-peak hours are more likely to arrive randomly. Moreover, Luethi et al. demonstrated that the arrival behavior is also dependent on service reliability (Luethi et al., 2007). This means that a control strategy enabling a reduction of headway variation will reduce passenger waiting times at stops.

#### 5.3.4 Direct Transfer (DT)

Scheduled synchronized transfers, such that two or more vehicles can meet at a transfer point can be improved by implementing a library of tactics. Missed transfers will increase total passenger travel time by the extra waiting time for the next vehicle. A successful synchronized transfer -direct transfer- occurs if the following holds:

$$\Gamma_1 = \text{if } A_{k,n,r} - D_{\dot{k},n,\dot{r}} > 0 \text{ then } 1, \text{ else } 0; \quad (5.8)$$

$$\Gamma_1 = \text{if } A_{\dot{k},n,\dot{r}} - D_{k,n,r} > 0 \text{ then } 1, \text{ else } 0; \quad (5.9)$$

where  $A_{k,n,r}$  and  $D_{k,n,r}$  are arrival time and departure time of vehicle trip  $k$  at stop  $n$  on route  $r$ ; subsequently DT occurs if  $\Gamma_1 + \Gamma_2 = 0$ .

On the other hand, missed transfers will increase total passenger travel time by the extra waiting time for the next vehicle. The waiting time at transfer stop,  $tp$ , is designated by the following formula:

$$W_{k,n,r}^{missed} = \left( 1 + \frac{p_{k,n,r\acute{r}}}{\sum_{n=1}^N \lambda_{n,\acute{r}} h_{k,n,\acute{r}}} \right) h_{k,n,\acute{r}} \quad (5.10)$$

where  $p_{k,n,r\acute{r}}$  is the number of transferring passengers from route  $r$  to  $\acute{r}$  at stop  $n = tp$ . It is assumed that passengers arrive at stop  $n$  on the route of  $\acute{r}$  randomly at a rate of  $\lambda_{n,\acute{r}}$ .

### 5.3.5 Library of Tactics

Operational tactics are usually applied to rectify the headway irregularity and to make sure that the deviation from the scheduled headways is maintained within a predefined tolerance. This is also done to maximize the simultaneous arrivals of vehicles to a given transfer point. Generally speaking, there is a set or 'library' of feasible operational tactics to be used by PT operators. At each control step a set of possible operational tactics is selected from the library of tactics. The optimal values of the selected operational tactics are determined according to defined objectives. The following section describes two control models that essentially follow this logic with the objective of minimizing headway variation at each vehicle trip.

- 1) *Speed-change control model:* Speed-change presents a control strategy that continuously adjusts the vehicles' speeds based on a cooperative two-way speed adjustment to achieve a proper headway between the front and back vehicles. Such a cooperative control is shown to be effective in preventing bunching. This headway-based dynamic speed-adjustment model determines optimal speeds by updating vehicle running speed and acceleration and deceleration rates on the basis of vehicles locations. Vehicles are allowed to change speed, but not above the speed limit. The model developed assumes vehicle speed and location given PT-related GPS information.

Because of the stochastic nature of PT systems, the speed-change tactic combined with other tactics delivers better results than the isolated use of the speed-change tactic (Liu et al., 2014). This is especially the case during peak hours and traffic

congestion. With the employment of the inter vehicles communication (IVC) systems, drivers can also communicate with each other through their communication coordinator, and can dynamically adjust their route-section travel speed (average section running time) in order to increase the encounter probability of vehicles at transfer points (Liu et al., 2014). The speed-change control formulation is based on the headway deviation definition of the expression given in Equation 5.4. In order to attain the desired headway, the speed should increase or decrease with deviation from the desired headway. When vehicles operated with evenly-distributed headways, the resulting spaces are equal to the desired space:

$$\bar{s}_{k,r} = v_{k,r}^d H_{k,r} \quad (5.11)$$

where  $v_{k,r}^d$  is the desired vehicle speed and  $H_{k,r}$  is the planned headway. The distance of the vehicle  $k$  to the desired space,  $\Delta s_{k,r}$  is extracted from the spacing between vehicles,  $s_{k,r}$ , and desired space,  $\bar{s}_{k,r}$  with the following expression:

$$\Delta s_{k,r} = s_{k,r} - \bar{s}_{k,r} \quad (5.12)$$

In Equation 5.12 if the value of  $\Delta s_{k,r}$  is a negative value, this means a vehicle tends to bunch with the vehicle in front of it. Consequently, from kinematic equations of motion, the speed control rule is formulated as follows:

$$v_{k,n,r}^c = \sqrt{\pm 2|a_{k,n,r}|\Delta s_{k,r} + v_{k,n,r}^2} \quad (5.13)$$

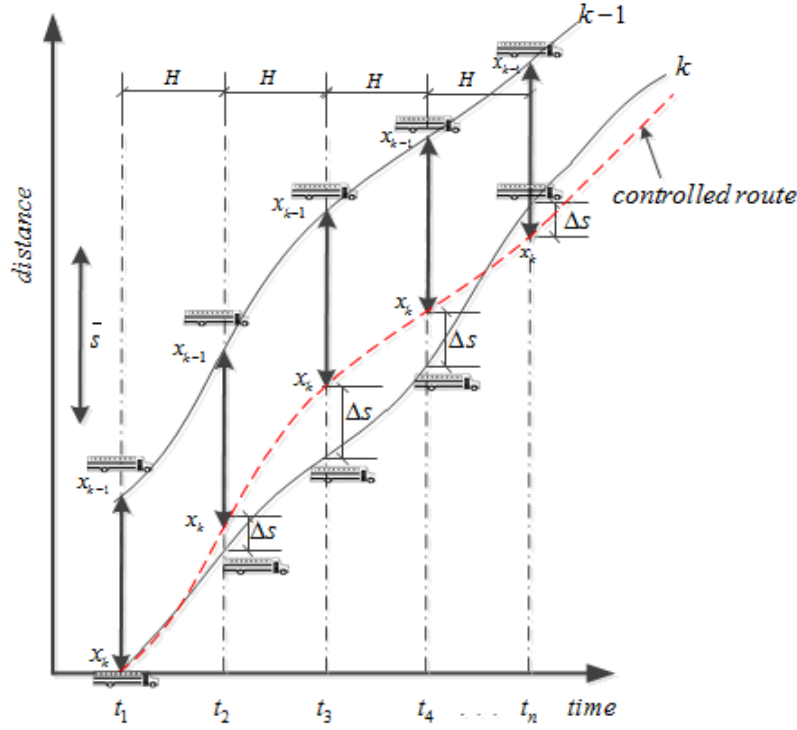
where  $v_{k,n,r}^c$  denotes new speed under control,  $a_{k,n,r}$  is desired rate at which speed would increase or decrease, in which plus means acceleration and minus means deceleration. This desired rate is extracted from the following formula:

$$a_{k,n,r} = \frac{2(\delta s_{k,r} - v_{k,n,r}\xi_{k,n,r})}{\xi_{k,n,r}^2} \quad (5.14)$$

By substituting Equation 5.14 into Equation 5.13, the result as the new speed based on the speed-change control is defined as:

$$v_{k,n,r}^c = \sqrt{\pm 4\left|\frac{\Delta s_{k,r} - v_{k,n,r}\xi_{k,n,r}}{\xi_{k,n,r}^2}\right|\Delta s_{k,r} + v_{k,n,r}^2} \quad (5.15)$$





**Figure 5.1:** Space-time diagram of PT operations.

This inter-stop control action can be utilized as complementary to other stop controls. Figure 5.1 illustrates a space-time diagram of PT operations.

- 2) *Holding control model:* Holding a vehicle at one stop is one of the most commonly-used control actions, in practice, to improve the on-time performance. Vehicle holding control strategies can usually be employed in two directions: headway-related and departure-time related. The first direction uses threshold-based control models in which vehicles are held at a control stop on the basis of the irregularity of their headway from the planned service headway (Osuna and Newell, 1972). The second direction uses models to determine the holding times on the basis of a schedule deviation. The schedule-based direction involves holding a vehicle only until its scheduled departure time. In this study, only those models of the first direction, headway-related control strategies, are considered. Thus, the holding time at the control stops is defined as:

$$HO_{k,n,r} = \min\left(\alpha E_{k,n,r}, HO_{k,n,r}^{max}\right) \quad (5.16)$$

where  $HO_{k,n,r}^{max}$  is the maximum holding time at stop  $n$  and  $\alpha$  is a constant value,

ranging from 0.0 to 1.0 for stability reasons and control strength.

Based on the Equation 5.16, the effect of holding tactic on the departure time and for the rest of trip is as follow:

$$D_{k,n,r} = D_{k,n-1,r} + c_{k,n,r} + d_{k,n,r} + HO_{k,n,r} \quad (5.17)$$

where  $D_{k,n,r}$  represents the departure time of vehicle on trip  $k$  at stop  $n$ ,  $c_{k,n,r}$  denotes the running time between stops  $n-1$  and  $n$ , and  $d_{k,n,r}$  is the dwell time of the vehicle at stop  $n$ . The following equation defines dwell time based on boarding,  $b_{k,n,r}$  and alighting,  $a_{k,n,r}$ , in which boarding is,  $b_{k,n,r} = \lambda_{n,r} h_{k,n,r}$ .

$$d_{k,n,r} = f_0 + f_1 b_{k,n,r} t_b + f_2 a_{k,n,r} t_a \quad (5.18)$$

where  $f_0$ ,  $f_1$  and  $f_2$  are estimated parameters for the dwell time function with either  $f_1 = 0$ , or  $f_2 = 0$  based on the input data used; that is  $f_2 = 0$  if the boarding time is longer than the alighting time, and vice versa for  $f_1 = 0$ . The passenger boarding and alighting times are  $t - b$  and  $t_a$ .

The main objective of a threshold-based holding control strategy is to regulate vehicle headways at the control stop based on a theoretical relationship between the expected waiting time of randomly arriving passengers and the variation of headways. In order to calculate the additional travel time, the model calculates the effect of headway-based holding on passengers' waiting time, in which a change in headways leads to a change in additional travel time for passengers. Thus, in-vehicle waiting time for passengers aboard,  $B_{k,n,r}$ , a vehicle being held at stop  $n$  on route  $r$  can be written in the following way:

$$W_{k,n,r}^{in-vehicle} = \left( 1 + \frac{B_{k,n,r}}{\sum_{n=1}^N B_{k,n,r}} \right) HO_{k,n,r} \quad (5.19)$$

where  $B_{k,n,r} = l_{k,n,r} + b_{k,n,r} - a_{k,n,r}$ ; the state variable of  $l_{k,n,r}$  represents passengers' load of vehicle trip  $k$  at stop  $n$  on route  $r$ . It should be noted that the checking constraint,  $B_{k,n,r} < Q_{k,r}^{max}$  is hold, where  $Q_{k,r}^{max}$  is passenger capacity of vehicle on route  $r$ .

- 3) *Total waiting time:* According to the formulations derived from the expected waiting times for passengers, the following expression for the proposed model should be minimized:

$$\min \sum_k \sum_n \sum_r \left( W_{k,n,r}^{stop} + W_{k,n,r}^{missed} + W_{k,n,r}^{in-vehicle} \right) \quad (5.20)$$

## 5.4 Simulation Experiments

To evaluate the system-performance in a systematic manner, a discrete event model is developed to simulate vehicle operations with controlled operating conditions. The theoretical model is generally built on assumptions to be analytically tractable. Some of these assumptions can be relaxed in the simulation, yielding a more realistic representation of a PT network operation. The simulation model adopts input and parameters from real-life data so that the performance of the library of tactics can be assessed under stochastic conditions.

### 5.4.1 Event-activity System Modelling

The system is simulated using an event activity (EA)-based and stochastic simulator. In the EA, the system changes state as events occur. Activities are undertaken to achieve a specified outcome or a service. They have duration and usually involve the use of process elements and resources (Kelton and Law, 2000). Three events are defined to describe the possible status of the vehicle: (i) departure of a vehicle from a stop (departure event); (ii) at time  $t$ , arrival of a vehicle to position  $x$  which is a location between two stops (position event), and (iii) arrival of a vehicle at a stop (arrival event). Two activities are defined to depict the process of a PT service on the model: (i) traveling on the route between consecutive stops (driving activity), and (ii) serving passengers at a stop (dwelling activity). Transferring is considered a part of dwelling activity at transfer point in which missed transfers should wait for the next vehicle. Each event is triggered every time a vehicle reaches a stop or position  $x$ . Vehicle loads, travel times and position, as well as the number of passengers waiting at each stop and transferring passengers are updated in each event. The simulation keeps track of individuals at the stops and

in the vehicle at each point in time. The operational tactic deployment process can then be divided into a sequence of decision stages based on events; minimize the gaps between the planed and actual headway, and minimize the total passenger waiting time. In this way the library of operational tactics helps to reduce not only vehicle bunching but also to increase the likelihood of direct transfers.

#### 5.4.2 Simulation Environment

A case study was simulated for analyzing and validating the performance of the model before and after implementation of the tactics. Moreover, the PT network has been simulated for handling the concept of synchronized transfers. The simulation software ExtendSim8 (ExtendSim, 2008), has been used to simulate the network. In the simulation, passengers arrive randomly following a Poisson distribution with mean  $\lambda_{n,r}$  at each stop. This distribution is common in service with headways of less than 12 min (Jolliffe and Hutchinson, 1975, Okrent, 1974). The boarding process follows a FIFO discipline. Thus, the earliest arriving passenger will be the first to board a vehicle if there is available capacity or will have to wait for the next vehicle if unavailable. The simulation model considers the vehicle travel times between two adjacent stops as a random variable with a log-normal distribution;  $LN(\mu, \sigma^2)$  that has been commonly used in previous studies (Andersson et al., 1979, Hickman, 2001). In the dwelling process, boarding and alighting take place at different doors. In the simulation, each passenger contributes the same marginal times when boarding and when alighting. The total dwell time is then estimated as the maximum time between these two processes.

### 5.5 Case Study

To assess the effect of applying different tactics in practice, a case study of Auckland, New Zealand's largest and busiest city, is analyzed. A case study for the Auckland region was based on AT (Auckland Transport) data, which consisted of the PT network, AT-HOP cards (Auckland Integrated Fares System) and a PT demand forecast. All buses of the Auckland transport network are equipped with AVL and GPS systems. These data are used to analyze bus travel times and headway adherence (to implement operational tactics). This means that real-time information on bus locations can be used to predict

bus arrivals at the transfer points and to determine bus headway deviations. Analysis was carried out on three bus routes and two transfer points. The first route, known as Northern Express (NEX), has a dedicated lane that runs from the suburbs to and across the Auckland CBD area; it transports a very large number of passengers during peak hours. The second route, Route 858, runs north-south (east of the first route) and the third route, Route 880, is a loop that serves as a feeder route.

### 5.5.1 Control Strategies(Policy)

Two different control policies were tested and compared. The first policy, "No-Tactics", was used for comparison purposes. That is, the vehicles are dispatched from the terminal at a designed headway without taking any control action along the route. In this policy, because of headway variation and vehicle bunching, direct transfers occurred infrequently. The second was the combination of "Holding and Speed-Changes".

### 5.5.2 Simulation Analysis

The proposed model was applied to the case study. Boarding and alighting times per passenger were set at 2.5 and 1.5 seconds, respectively. Vehicle capacity was given as 60 passengers, with 40 seated and 20 standing. Headways are set to 5, 10, and 5 minutes for routes 1, 2, and 3 with an evenly scheduled headway per route.

- 1) *Scenario:* For the scenarios, two demand profiles were tested in this analysis: the base demand profile is the afternoon peak passenger demand obtained through the AT-HOP cards system; the second profile was created by doubling the demand rates of the base case to simulate high-demand scenarios. Table 5.1 indicates the average number of passengers per simulation in each scenario as well as the designed headway for each route. For each scenario, the model was run for six hours. The first hour of simulation was always discarded to minimize the initial condition impact and allow the model time to stabilize (warm-up period).

The minimum and maximum headway variations, as the boundary for triggering an intervention, were set to  $\pm 20\%$ . Thus, for 5 minutes headway, headways less than 4 minutes and more than 6 minutes are considered as earliness and tardiness

**Table 5.1:** Route characteristics

Route	Headway (min.)	Average number of passengers	
		Scenario1	Scenario2
1	5	257	514
2	7	1342	2648
3	5	958	1916

respectively. Based on Molnar (2008), bunching is considered where the headway between buses is less than or equal to two minutes.

2) *Performance:* In order to evaluate system's reliability, the performance of the control strategies is assessed. System reliability is represented by headway variance, which is calculated across all vehicle trips and stops. Undoubtedly, lower headway variance results in lower passenger waiting times and indicates greater system reliability. Subsequently, four performance measures are used to compare between all control strategies: passenger wait time at stop, passenger in-vehicle time, transfer waiting time and vehicle travel time. The efficiency of the system was evaluated by means of control strength for different reduction levels. Thus, the control strength for earliness was set to  $\alpha = 0.5$  (half control),  $\alpha = 0.75$  (semi-full control) and  $\alpha = 1$  (full control). The constant value for tardiness is set to  $\beta = 1$ .

## 5.6 Analysis of the Results

The performance of the Auckland system was evaluated by means of total passengers waiting time. The following subsections describe results of the performance indicators according to the developed simulation model.

### 5.6.1 Average Waiting Times, Standard Deviations, and Bunching

Table 5.2 describes the passengers waiting times for each scenario given the two types of control policies. This table presents the average value for waiting times with their respective standard deviations, and the percentage improvement of the combined tactic over the No-Tactics ("None") policy. The results demonstrated the significantly better performance of the proposed control policy, in both scenarios. A summary of the

performance measures shows that the tactics-based control policy presents a much more stable performance with standard deviations meaningfully lower than the no-control policy. The table shows greater service enhancement through a reduction in total waiting time in the scenario with base demand profile (#1). This suggests that if the demand rate is not too high, the use of the presented tactics can decrease waiting times and drastically increase the likelihood of direct transfers.

**Table 5.2:** Service performance under two scenarios

	Scenario 1				Scenario 2				
	None	H-SC		None	H-SC		$\alpha = 0.5$	$\alpha = 0.75$	$\alpha = 1$
		$\alpha = 0.5$	$\alpha = 0.75$		$\alpha = 0.5$	$\alpha = 0.75$			
$W^{stop}$	7828.32	3669.45	2698.74	2417.39	11342.16	5918.34	4784.12	5143.67	
SD	712.33	174.09	76.22	42.81	1345.29	311.48	85.23	112.78	
Improvement%		53.13	65.53	69.12		47.82	57.82	54.65	
$W^{in-vehicle}$	182.4	645.31	821.84	1105.26	298.32	942.34	1362.31	1613.87	
SD	34.21	69.52	95.32	122.33	86.20	101.25	93.21	162.05	
Improvement%		-253.75	-350.52	-505.89		-215.88	-356.66	-440.99	
$W^{missed}$	1345.74	504.82	341.85	114.33	2224.31	631.12	445.80	383.52	
SD	945.12	156.11	90.24	19.32	873.26	91.85	61.25	26.12	
Improvement%		62.49	74.60	91.50		71.63	79.96	82.76	
Total	9356.48	4819.58	3862.42	3636.97	13864.79	7491.80	6592.23	7141.05	
SD	1183.99	243.95	151.78	131.03	1606.18	340.16	140.37	199.15	
Improvement%		48.49	58.72	61.13		45.97	52.45	48.50	
Bunching (%)	26.32	9.25	3.93	3.07	35.62	14.23	8.34	6.81	
Improvement%		64.86	85.07	88.34		60.05	76.59	80.88	

Note: H-SC = Holding and Speed-Change.



In addition, from Table 5.2, better results were obtained when applying the tactic with  $\alpha = 1$ , and  $\alpha = 0.75$  in Scenarios #1 and #2 with 61.13% and 52.45% improvement of total waiting times, respectfully. This indicates that applying semi-full control strength ( $\alpha = 0.75$ ) in high-demand case results in shorter passenger waiting times and indicates greater system reliability. On the other hand, in Scenario #1, a somewhat superior outcome is observed with only a 2.41% greater value for full control strength ( $\alpha = 1$ ). However, Table 5.2 shows that the in-vehicle waiting time can be increased from 821.84 to 1105.26 seconds or from 1362.31 to 1613.87 seconds when taking the full strength control into account. The implication of this pattern suggests that it may not be necessary to consider the control strength rigorously as long as the improvement is not significant.

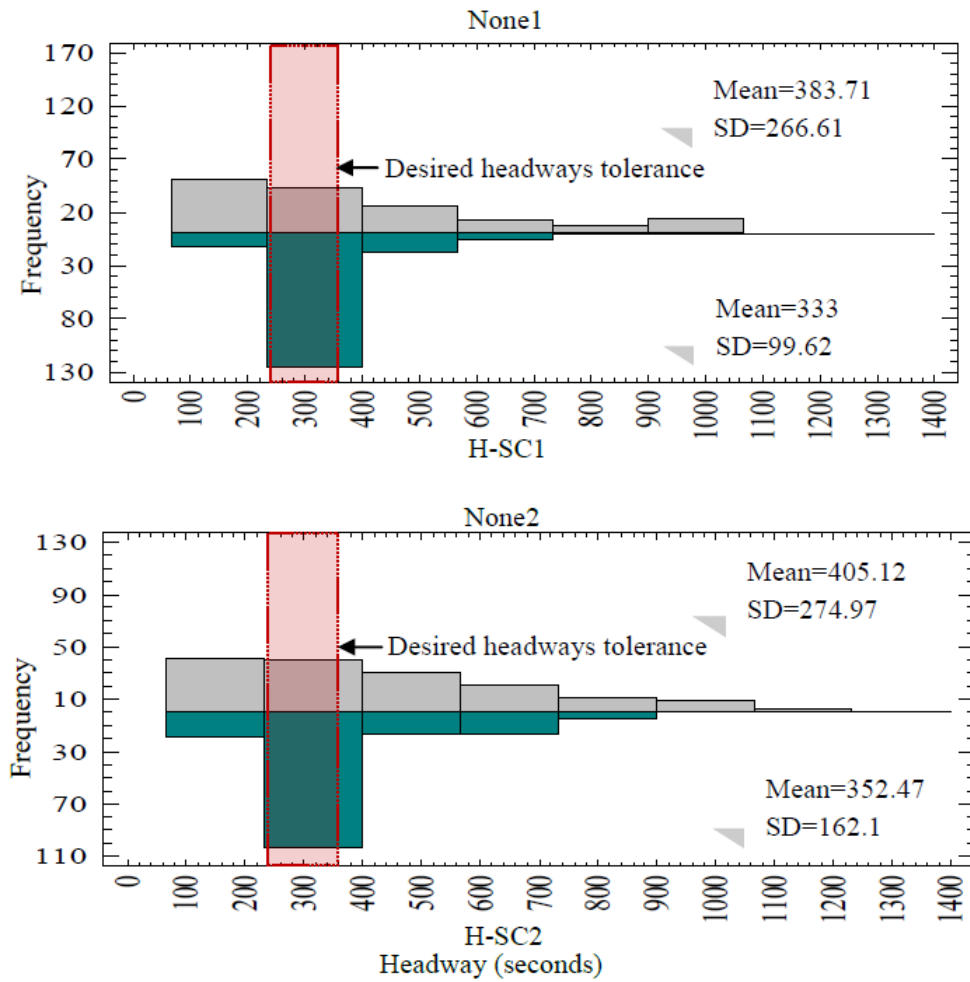
As the aim of the implementation of tactics was mainly to synchronize the arrival of transit vehicles at a transfer area, the results show a significant improvement in the likelihood of direct transfers resulting from the use of control policies in both scenarios. Again, the base demand scenario yielded the best results as expected, by 91.5% reduction in missed transfer waiting times.

In terms of bunching, Table 5.2 demonstrates greater service enhancement through the control policy in vehicle bunching with an 88.34%, and 80.88% improvement in Scenarios #1 and #2 respectively.

### 5.6.2 Headway Distribution

Based on the proposed simulation model, it is also possible to monitor the headway variation for a typical simulation run. Vehicle bunching takes place when headways between vehicles are irregular. Identifying and understanding the distribution and attributes of vehicle bunching helps to ensure appropriate control strategies. The simulation results illustrate the headway frequency distribution, over hours of simulation and stops along a route. Route 858 was selected because this route is the longest route of the case study and is long enough for vehicle bunching to appear with 5 minutes headway.

The results demonstrated greater service enhancement through a reduction in headway variations in both scenarios by the use of suggested operational tactics. This can be observed graphically in Figure 5.2, which illustrates the headway distribution before and

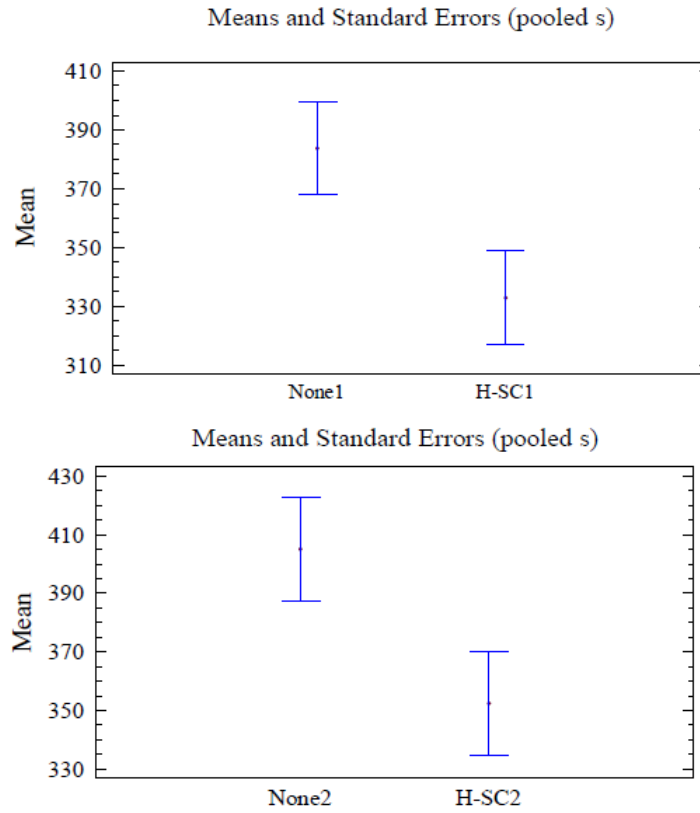


**Figure 5.2:** Headway distributions for two scenarios under two control policies.

after applying the tactics. Generally, the results also show a better outcome for base-demand scenario than high-demand scenario through a reduction in headway variation. This suggests that the use of tactics drops standard deviation to 99.62 seconds, a reduction of 167 seconds in the base-demand scenario. Similarly, it drops to 162.11, a reduction of 112.9 seconds in the high-demand scenario. It may also be observed from Figure 5.2 that by implementing tactics, the actual headways can be kept close to the desired headways tolerance more frequently.

### 5.6.3 Effectiveness of Performance

In order to statistically understand the significance of the PT service improvement, the "sample comparison" test was used to construct the standard errors interval for both control policies. This analysis can be used to test whether differences between

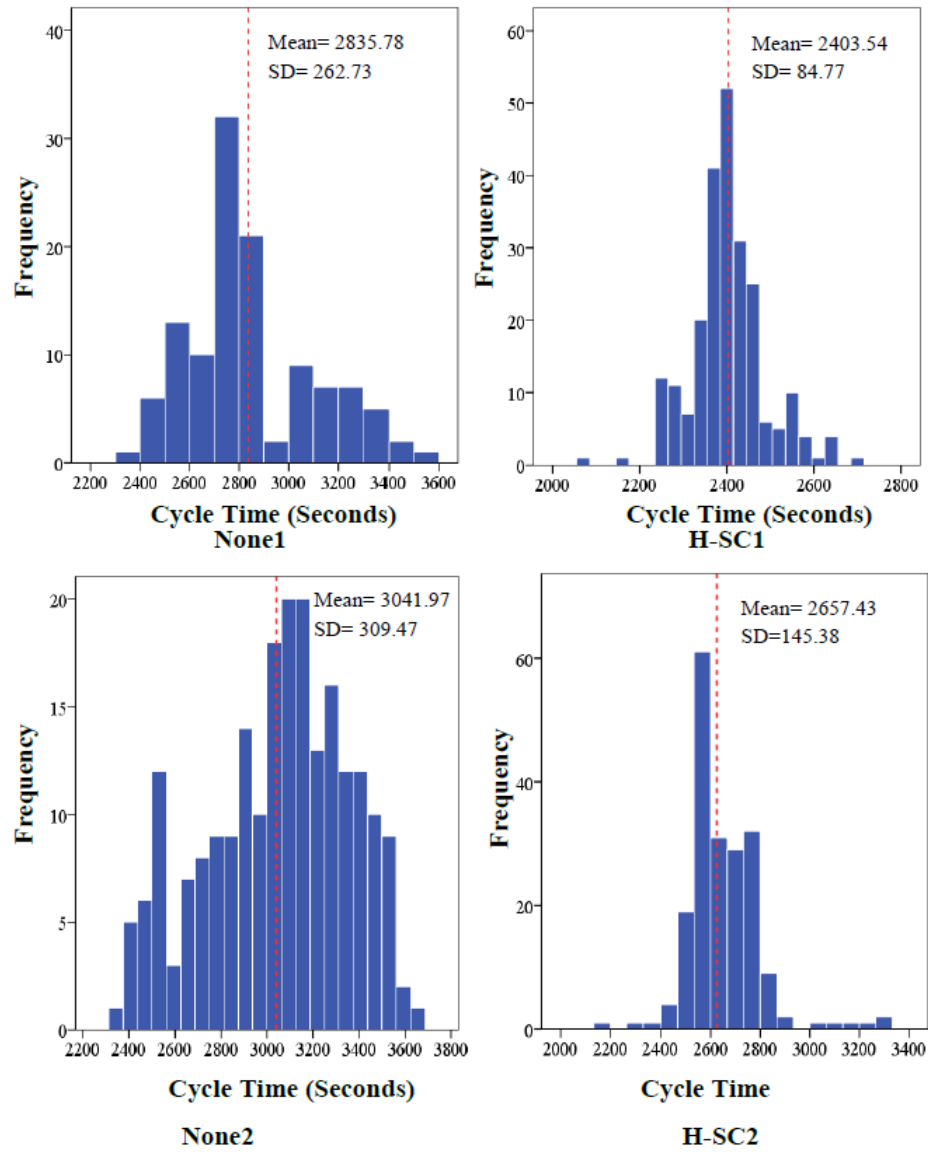


**Figure 5.3:** Headway means comparison for two scenarios.

two samples are statistically significant (confidence interval of 95%). The results show that no samples overlap. This indicates that applying the tactics attains a statistically significant improvement as appears in Figure 5.3.

#### 5.6.4 Cycle Time Distribution

In order to explore the service reliability of the system under the presented scenarios, the cycle time of vehicle trips was evaluated. Figure 5.4 shows the distribution observed for cycle times across all vehicles for the two different control strategies on Route 858. The results depict that H-SC1 (holding and speed-change in Scenario#1) presents the smallest average cycle time and the lowest variability across all strategies. The results revealed that while a no-control policy shows an average cycle time of 2,835.78 seconds, the holding and speed-change policy drops it to 2,403.54, a reduction of 15.24% in Scenario #1. Similarly, in Scenario #2, the holding and speed-change policy shows an average cycle time of 2,657.43 seconds, a reduction of 12.64% compared with the no-control policy.



**Figure 5.4:** Cycle time distribution for both scenarios.

## 5.7 Conclusions

Public transport (PT) reliability largely depends on the distribution of the scheduled vehicle headways, often referred to as PT on-time performance. In many instances the observed headway reaches values outside a desired tolerance because of the stochastic nature of passenger demand, including unexpected events, traffic conditions and driver's behavior. These variations of headways will create the undesirable vehicle (especially bus) bunching phenomenon unless a proper control action is taken. This study develops a methodology to attain optimally real-time control actions so as to minimize the bunching phenomenon. To this end, a 'library' of selected operational tactics is constructed, for

the PT operator, to assist in reducing not only vehicle bunching, but also to increase the likelihood of direct (without wait) transfers. This work uses simulation tools in order to identify optimal settings by which a combination of holding and speed-changes tactics could be efficiently implemented. The simulation model is illustrated through a detailed case study of a PT network from Auckland, New Zealand. The simulation uses two demand scenarios: data-based Scenario 1, and a simulated high-demand Scenario 2. Following are general conclusions of the simulation results attained.

1. The tactic-based control strategy always results with a significant lower standard deviation of the scheduled headways than the no-control strategy.
2. Applying semi-control strength in Scenario 2 results with a significant lower passenger waiting time than in the no-control strategy. For Scenario 1 the semi-control and full-control strengths yield close results.
3. Vehicle bunching situations are reduced significantly by the use of the tactic-based control strategy.
4. The results show a better outcome of reducing headway variations for Scenario 1 (base-demand) than Scenario 2 (high-demand).
5. The control tactics using Scenario 1 exhibit smaller average cycle time and lower variability of the reliability measures than when using Scenario 2.

Finally the analysis shows that the developed combination of operational tactics is sensitive to changes of passenger demand at high-demand levels; this is related to changes in reducing passenger wait time, in-vehicle time, transfer waiting time, number of bunching situations and vehicle cycle time. In other words, operators should pay attention to the level of passenger demand when using operational tactics, especially with full-control strength. Future research may continue to develop an extended list of operational tactics within the considered library of tactics, and investigate further scenarios of high passenger demands.

The next chapter explains a real-time tactic-based control (TBC) procedure to increase PT service reliability in headway-based system.

## Chapter 6

# Synchronized Transfers in Headway-Based Public Transport Service Using Real-Time Operational Tactics

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(Nesheli and Ceder, 2016)

### 6.1 Abstract

The problem of applying efficient vehicle synchronization into transfer points is addressed. In order to reduce passenger transfer waiting time and provide an integrated, well connected, public transport (PT) service, maximal synchronized transfers are employed at the planning level. However, at the operation level, synchronized transfers do not always appear because of certain stochastic and uncertain factors, such as traffic disturbances and disruptions, fluctuations of passenger demand and erroneous behavior of PT drivers. This can lead to deterioration in system reliability, missed transfers, and passenger frustration. This work presents a real-time tactic-based control (TBC) procedure to increase the service reliability and actual occurrence of synchronized transfers in headway-based PT

system. The procedure aims at minimizing additional travel time for passengers and reducing the uncertainty of meetings between PT vehicles. The TBC utilizes selected online operational tactics, such as holding, boarding limit, and skip-stops, all of which are based on real-time data. A library of operational tactics is firstly built to serve as a basis of the real-time decision making process in the TBC. Then, an extensive event-based activity simulation analysis framework with dynamic moving elements is constructed to represent the logical process of the PT transfer synchronization problem. A case study of the Auckland PT system is described for assessing the methodology developed. The results show improvements of system performance and yielded new findings on what control policy to use in different scenarios.

## 6.2 Introduction

Fundamentally, it is desirable to provide frequent and regular service in most public transport (PT) systems (Osuna and Newell, 1972). However, in actual field implementation, due to some uncertain and unexpected exogenous factors, PT services are not regular. The irregularity of PT service leads to missed transfers, one of the undesirable features of PT service, as it causes increased passenger waiting and travel times, and consequently, passenger frustration.

Studies (Barnett, 1974, Newell, 1974, Osuna and Newell, 1972) showed, however, that to provide regular service when uncertainties are present, utilizing control actions is inevitable. Newell and Potts (1964) discussed the implications of no use of control strategies whereby even a very small disturbance can cause serious off-schedule running. This deviation will be amplified and propagated along the route, causing service deterioration and vehicle bunch up. For these reasons, and in order to control the inherent randomness in PT systems, control strategies, such as holding, skip-stop, boarding-limit and short turn, are used at the operations phase (Ceder, 2007, 2015).

Osuna and Newell (1972) developed a single point holding strategy in an idealized PT system. They formulated the control process as a dynamic programming problem to minimize the average passenger waiting time. Barnett (1974) investigated holding vehicles strategy at a selected control stop where average passenger waiting time and average in-vehicle passenger delay are considered. Eberlein et al. (1999) studied a group of control

actions -deadheading, expressing and holding strategies- singly and in combination. They used heuristic algorithms to solve the combined control problem. Hickman (2001) formulated the holding problem as a convex quadratic program and developed an analytic stochastic model. Thereafter, Sun and Hickman (2005) investigated the possibility of implementing a stop-skipping policy for operational control in real-time. A nonlinear integer programming problem for two different stop-skipping policies was formulated to examine how the performance of the two policies changed with the variability of effective parameters on the route. Hadas and Ceder (2008) proposed a dynamic programming model to compute the effects of control tactics on the number of synchronized transfers and total passenger travel time. Delgado et al. (2012) developed holding and boarding-limit strategies. A deterministic mathematical model with a nonlinear and non convex objective function was proposed for real-time transit operations. Finally, Muñoz et al. (2013) investigated dynamic control strategies for PT operation with real-time headway-based control, comparing different approaches to different scenarios.

With the advent of new technologies such as: AVL (Automatic Vehicle Location), APC (Automated Passenger Counting), and real-time PT information, many simulation models were developed by researchers. Transit simulations provide a dynamic perspective on transit operations, enabling comparisons of various scenarios and representation of complex interactions between the network components (Cats et al., 2010). Dessouky et al. (2003) developed simulated systems that employed holding and dispatching strategies. The results showed that advanced technologies were most advantageous when there were many connecting buses. The schedule slack was then close to zero. Fu and Yang (2002) investigated both the threshold based holding control model and an optimal holding control model by considering a vehicle's preceding as well as following headways. Based on a simulation, the study indicated that the control point should be placed at the bus stop with high demand and located close to the middle of the route, and that real-time bus location information can help reduce passenger in-vehicle time and bus travel time when a number of control points are used. A dynamic transit simulation model, Bus Mezzo, is proposed by Cats et al. (2011) to investigate the holding strategy. They considered the interaction of passenger activity, transit operations, and traffic dynamics in their model. The recent study by Ji and Zhang (2013) also proposes a robust dynamic control strategy to regulate bus headways and to prevent buses from bunching by holding them at bus stops. They develop a controlling method with the aid of a simulation process to



produce better system reliability than do some of the existing control strategies.

Although extensive research has been conducted to analyse PT movements at a one-way loop transit corridor, to date there are some real-time control problems, not yet addressed, about their actual use. The main problems are: (i) in previous studies, researchers employed only one or two operational tactics where, in fact, a group of operational tactics can be used, (ii) the PT network structure of previous studies was not complex; it includes only one route or a small unidirectional network with the link's travel time assumed to be deterministic, thus not so realistic, and (iii) few studies investigated the use of real-time automatic data collection systems and the challenge of implementing them with real-time control actions in the real-life example. The rapid development of information (more reliable and accurate data) and current technology, especially the intelligent transportation system, open the door to use operational tactics in real time and online.

Previous studies by Hadas and Ceder (2010a), Liu et al. (2015), Nesheli and Ceder (2014) and continuing along this line Nesheli and Ceder (2015b) showed that by using some selected operational tactics, the frequency of direct-transfers (without wait) can be significantly improved and the total passenger travel time can be reduced. In this work we focus on the development of a new real-time tactic-based control (TBC) procedure to increase the service reliability and actual occurrence of synchronized transfers in headway-based PT system. The procedure aims at minimizing additional travel times for passengers and reducing the uncertainty of meetings between PT vehicles.

The rest of the paper is organized as follows: first, the overall framework and implementation details of the PT system control model are presented. The application of the PT simulator is demonstrated with implementation for a high-demand PT network in Auckland, New Zealand. The analysis of the case study includes performance analysis and study of control effectiveness. The headway distribution shows the impact of control policy on the performance. Finally, the conclusion and recommendations for future study are presented.

### 6.3 System Control Models

PT control strategies can be designed in various forms with a major differentiating characteristic being how a control action is triggered. In this section, the main headway-

based control strategies and their associated key variables are described. The mathematical models including the effect of each control action on waiting time for passengers are investigated.

### 6.3.1 System Characteristics

The system underlying the model consists of main and feeder routes. The transfers occur at separate transfer points for each route. The service area includes  $n = 1, 2, \dots, N$  stops and  $r = r, \acute{r}, \dots, R$  routes. A route is made up of a collection of "trips"; each trip  $k$  represents a single vehicle run, based on a certain departure time, along the series of stops on the route.

### 6.3.2 Headway-based Model Description

The main objective of a headway-based control model is to regulate the vehicle headway at the control stop. The headway-based control method requires less slack than the schedule-approach to maintain the headway within a given tolerance (Daganzo, 2009). That is, the PT system operates faster by means of headway-based control. In a deterministic and stationary world with no random variation, vehicles arrival to stops would simply be regular when the planned headway is  $H$ . In reality, however, because of certain stochastic and uncertain factors, such as traffic disturbances and disruptions, fluctuations of passenger demand and erroneous behaviour of PT drivers give rise to deviations between the actual vehicle arrival times  $A_{k,n,r}$ , and those scheduled. As a result, actual headways,  $h_{k,n,r} = (A_{k,n,r} - A_{k-1,n,r})$ , differ from those planned, and this affects PT service performance, since longer headway deviation implies longer passenger waiting times. To model these effects in a simple way, headways variation within a given tolerance is determined. This gives the following expressions for the headway variation related to earliness ( $E$ ) and tardiness ( $T$ ):

$$E_{k,n,r} = \max[(\min H_{k,r} - h_{k,n,r}), 0] \quad (6.1)$$

$$T_{k,n,r} = \max[(h_{k,n,r} - \max H_{k,r}), 0] \quad (6.2)$$

where  $H_{k,r}$  is the planned headway with its "min" and "max" as the boundary for triggering an intervention (applied tactic). Thus, it is useful to define a state variable,  $\xi_{k,n,r}$ , that is the deviation of the headway of vehicle trip  $k$  at stop  $n$  from the desired headway:

$$\xi_{k,n,r} = \alpha E_{k,n,r} + \beta T_{k,n,r} \quad (6.3)$$

The constants  $\alpha$  and  $\beta$  characterize the policy and the sensitivity of control. Overall, maintain regular vehicle headway and keep the system running on time, the following expression is defined:

$$Z = \sum_k \sum_n \sum_r \xi_{k,n,r} \quad (6.4)$$

A control model is adopted to minimize  $Z$  by implementing proper tactics from a library of selected operational tactics on each PT trip for different events. To evaluate the additional travel time per passenger because of unreliable service, the waiting time at the stops should be considered. The expected waiting time for randomly arriving passengers (5) with headways of no more than 10-12 minutes can be calculated as:

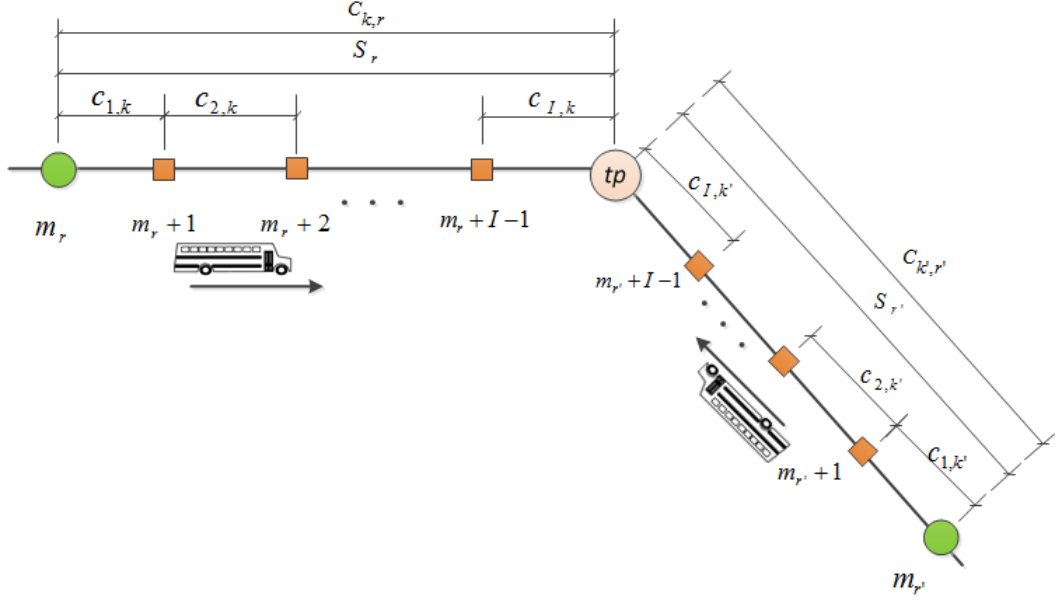
$$W_{k,n,r}^{stop} = \frac{H_{k,r}}{2} \left( 1 + \frac{\sigma^2(h_{k,n,r})}{H_{k,r}^2} \right) \quad (6.5)$$

where

$W_{k,n,r}^{stop}$  = average waiting time at a stop;

$\sigma^2(h_{k,n,r})$  = variance of headway at a stop.

Equation 6.5 reflects that the delay caused by headway variation contributes incrementally to passenger waiting time at stops. That  $\gamma_{n,r}$  is a dimensionless measure of the demand



**Figure 6.1:** Graphical representation of the PT network.

rate at stop  $n$ , equivalent to the ratio between the passenger arrival rate  $\lambda_{n,r}$  (in passengers/minute) and passengers' boarding rate (also in passengers/minute). Thus, the passengers boarding time at stop  $n$  increases by if the headway increases by one unit time.

$$W_{k,n,r}^{stop} = (1 + \gamma_{n,r}) \left[ \frac{H_{k,r}}{2} \left( 1 + \frac{\sigma^2(h_{k,n,r})}{H_{k,r}^2} \right) \right] \quad (6.6)$$

### 6.3.3 Direct Transfer

Scheduled synchronized transfers, so that two or more vehicles can meet at a transfer point, can be improved by implementing a library of tactics. Missed transfers will increase total passenger travel time by the extra waiting time for the next vehicle. Consider a PT system having one transfer point and two routes. A route is divided into " $I$ " segments with  $c_{1,k}, c_{2,k}, \dots, c_{I,k}$  running times between stop  $n$  and stop  $n+1$ . Accordingly  $\nu_{k,n}$  denotes vehicle speed on tip  $k$  to a transfer point. This is shown in Figure 6.1. The possible direct transfer (DT) occurs if two or more PT vehicles, meet at the same time at a transfer point, which is based on the following theoretical relationship between the total trip times of vehicle arrivals at transfer point:

$$S_r = \frac{1}{2} \bar{a}_{k,r} C_{k,r}^2 + v_{0,k,r} C_{k,r} \quad (6.7)$$

where

$S_r$  = distance travelled of route  $r$  from positional point to a transfer point;

$C_{k,r}$  = total trip time of vehicle on route  $r$  from positional point to a transfer point;

$\bar{a}_{k,r}$  = average acceleration of vehicle on route  $r$  (the plus sign means acceleration and the minus sign means deceleration);

$v_{0,k,r}$  = initial speed of vehicle on route  $r$ ; it is to note that usually the initial speed equals zero, thus, we neglect this speed in the formulation. Based on the above notation, the average acceleration which is the change in the vehicle speed to the change in time can be obtained as:

$$\bar{a}_{k,r} = \frac{\sum_{i=m_r \in N}^{I=tp} \frac{\Delta v_{i,k}}{c_{i,k}}}{I} \quad (6.8)$$

where  $m_r$  is a positional point of route  $r$ , and  $tp$  is a transfer point. The running time in Equation 6.8 can be extracted from Equation 6.9 in which is the average running time.

$$c_{k,n,r} = \xi_{k,n,r} + \bar{c}_{k,n,r} \quad (6.9)$$

In addition from Equation 6.7 the total trip time obeys:

$$C_{k,r} = \frac{\sqrt{2\bar{a}_{k,r}S_r}}{\bar{a}_{k,r}} \quad (6.10)$$

This can be simplified to:

$$C_{k,r} = \sqrt{\frac{2S_r}{\bar{a}_{k,r}}} \quad (6.11)$$

This equation can be written for route  $\acute{r}$  by:

$$C_{k,\acute{r}} = \sqrt{\frac{2S_{\acute{r}}}{\bar{a}_{k,\acute{r}}}} \quad (6.12)$$

Thus the possible direct transfer occurs if the following holds:

$$C_{k,r} = C_{k,\acute{r}} \quad (6.13)$$

By substituting Equation 6.8 into Equation 6.11 and then rewriting Equation 6.13, we can define the result as the dimensionless measure of the acceleration or deceleration rate of the vehicle, equivalent to the ratio between the distance rate to a transfer point.

$$\frac{S_r}{S_{\acute{r}}} = \frac{\bar{a}_{k,r}}{\bar{a}_{k,\acute{r}}} \quad (6.14)$$

Following from Equation 6.9 and 6.14, keeping the distance ratio and acceleration ratio stable for different routes, undoubtedly assists in making direct transfers. To further enhance performance, the strategy will allow these intervals to be monitored as frequently as desired.

It is now possible to measure the effect of making or missing synchronized transfers on the change in passengers additional travel time by the definition of direct transfers. Therefore, a direct transfer occurs if the following holds:

$$\Gamma_1 = \text{if } A_{k,n,r} - D_{k,n,\acute{r}} > 0 \text{ then } 1 \text{ else } 0; \quad (6.15)$$

$$\Gamma_2 = \text{if } A_{k,n,\acute{r}} - D_{k,n,r} > 0 \text{ then } 1 \text{ else } 0; \quad (6.16)$$

where  $A_{k,n,r}$  and  $D_{k,n,r}$  are arrival time and departure time of vehicle trip  $k$  at stop  $n$  on route  $r$ , subsequently  $DT$  occurs if  $\Gamma_1 + \Gamma_2 = 0$ .

Accordingly, missed transfers will increase total passenger travel time by the extra waiting time for the next vehicle. The waiting time at transfer stop,  $tp$ , is designated by the following formula:

$$W_{k,n,r}^{missed} = \left( 1 + \frac{p_{k,n,r\acute{r}}}{\sum_{n=1}^N \lambda_{n,\acute{r}} h_{k,n,\acute{r}}} \right) h_{k,n,\acute{r}} \quad (6.17)$$

where  $p_{k,n,r\acute{r}}$  is the number of transferring passengers from route  $r$  to  $\acute{r}$  at stop  $n = tp$ . It is assumed that passengers arrive at stop  $n$  on the route of  $\acute{r}$  randomly at a rate of  $\lambda_{n,\acute{r}}$ .

### 6.3.4 Holding Control Model

Hold of a vehicle at stop is one of the most commonly used control actions in practice to improve on-time performance. In this model, the actual headway of the vehicle under control is compared with a planned headway and the amount of holding time is determined accordingly. The implementation of this control model is relatively simple. Only the arrival time of each vehicle at the control stop needs to be recorded. Thus, the holding time at the control stops is defined:

$$HO_{k,n,r} = \min\left(\alpha E_{k,n,r}, HO_{k,n,r}^{max}\right) \quad (6.18)$$

where  $HO_{k,n,r}^{max}$  is the maximum holding time at stop  $n$  and  $\alpha$  is a constant value, ranging from 0.0 to 1.0 for stability reasons and control strength.

On the other hand, the main objective of this study is to regulate vehicle headway in order to increase the likelihood of direct transfers. Therefore, if transfer points at the major stations of the PT system are chosen for the holding point, the holding time at these stops are described as:

$$HO_{k,n,r} = \begin{cases} \max\left(\omega_{k,tp,\acute{r}}, \min\left(\alpha E_{k,n,r}, HO_{k,n,r}^{max}\right)\right), & \text{if } \omega_{k,tp,\acute{r}} \leq HO_{k,n,r}^{max} \\ \min\left(\alpha E_{k,n,r}, HO_{k,n,r}^{max}\right), & \text{otherwise} \end{cases} \quad (6.19)$$

where  $\omega_{k,tp,\acute{r}}$  denotes the travel time for vehicle trip  $k$  on route  $\acute{r}$  to travel from its current location to the transfer point of  $tp$ . This time can be calculated when the vehicle on route  $r$  is arriving at the transfer point.

Based on the above equations, the effect of holding tactic on the arrival time  $A_{k,n,r}$  and for the rest of trip is defined:

$$A_{k,n+1,r} = A_{k,n,r} + c_{k,n,r} + d_{k,n,r} + HO_{k,n,r} \quad (6.20)$$

where  $c_{k,n,r}$  denotes the running time between stops  $n$  and  $n + 1$ , and  $d_{k,n,r}$  is the dwell time of the vehicle at stop  $n$ . The following equation defines dwell time based on boarding,  $b_{k,n,r}$  and alighting,  $a_{k,n,r}$ , in which boarding is,  $b_{k,n,r} = \lambda_{n,r} h_{k,n,r}$ .

$$d_{k,n,r} = f_0 + f_1 b_{k,n,r} t_b + f_2 a_{k,n,r} t_a \quad (6.21)$$

where  $f_0$ ,  $f_1$  and  $f_2$  are estimated parameters for the dwell time function with either  $f_1 = 0$ , or  $f_2 = 0$  based on the input data used; that is  $f_2 = 0$  if the boarding time is longer than the alighting time, and vice versa for  $f_1 = 0$ . The passenger boarding and alighting times are  $t - b$  and  $t_a$ .

To calculate the additional travel time, the model calculates the effect of headway-based holding on passengers' waiting time, in which a change in headways leads to a change in passenger travel time. Thus, in-vehicle waiting time for passengers aboard,  $B_{k,n,r}$ , a vehicle being held at stop  $n$  on route  $r$  can be written in the following way:

$$W_{k,n,r}^{in-vehicle} = \left( 1 + \frac{B_{k,n,r}}{\sum_{n=1}^N B_{k,n,r}} \right) H O_{k,n,r} \quad (6.22)$$

where  $B_{k,n,r} = l_{k,n,r} + b_{k,n,r} - a_{k,n,r}$ ; the state variable of  $l_{k,n,r}$  represents passengers' load of vehicle trip  $k$  at stop  $n$  on route  $r$ . It should be noted that the checking constraint,  $B_{k,n,r} < Q_{k,r}^{max}$  is hold, where  $Q_{k,r}^{max}$  is passenger capacity of vehicle on route  $r$ .

### 6.3.5 Boarding-limit Control Model

A boarding-limit tactic can be applied to regulate the vehicle headway at the stop in case of a route in high demand. Increased variance of headways and of passenger load at one stop leads to a higher variance in the subsequent stop. Nonetheless this boarding-limit tactic can be a complementary control action for holding to further reduce headway variation when the demand and travel times vary randomly. Those who benefit from the boarding-limit tactic are those who are currently on the vehicle and those who will board the vehicle in the future. The time saving for them is dwell time. To evaluate the additional travel time due to the applied boarding-limit tactic, the following expression based on extra waiting time for passengers prevented to board is defined:



$$W_{k,n,r}^{extra} = \left(1 + \frac{g_{k,n,r}}{\sum_{n=1}^N \lambda_{n,r} h_{k,n,r}}\right) \left(h_{k+1,n,r} + \left(1 - \frac{Q_{k,n,r}}{Q_{k,r}^{max}}\right)\right) \quad (6.23)$$

where  $g_{k,n,r}$  represents the number of passengers prevented to board vehicle trip  $k$  at stop  $n$ , and  $Q_{k,n,r}$  is used capacity of vehicle trip  $k$  when departing stop  $n$ . The value of  $(1 - \frac{Q_{k,n,r}}{Q_{k,r}^{max}})$  indicates the penalty for passengers who are not allowed to board if there is available capacity. For the holding tactic the  $g_{k,n,r}$  are assumed to take a zero value if the vehicle capacity is not binding, however, when the vehicle capacity is reached it corresponds to the number of passengers prevented from boarding due to capacity constraints.

### 6.3.6 Skip-stop Control Model

In a recent study Nesheli and Ceder (2014) investigated the formulation and properties of skip-stop/segment with the change in total passenger travel time. This study demonstrated that when a major disruption occurs, holding a vehicle, as the only tactic used, cannot guarantee obviating headway variation and schedule deviations. It is also the case when attempting to attain direct transfers. The skip-stop tactic comes to assist in control of the headways. The advantage of skip-stop is for passengers who are already aboard the vehicle and those who will board downstream. On the other hand, it has an adverse effect on passengers who want to board at the skipped stop and should wait for the next vehicle. This tactic is constrained by passengers who want to get off the vehicle at a planned stop to be skipped. The skipped passenger waiting time of vehicle trip  $k$  at stop  $n$  is described as:

$$W_{k,n,r}^{skipped} = \left(1 + \frac{q_{k,n,r}}{\sum_{n=1}^N \lambda_{n,r} h_{k,n,r}}\right) h_{k+1,n,r} \quad (6.24)$$

where  $q_{k,n,r}$  represents the number of passengers skipped and should wait for the next vehicle to bring them to their destination. It is assumed that the next vehicle is not allowed to skip the stop. It is also assumed that where passengers want to transfer the stop cannot be skipped.



### 6.3.7 Additional Travel Time

To evaluate the additional travel time ( $ATT$ ) for passengers, the model calculates the effect of the headway-based method on headways. A change in headway will lead to a change in passenger waiting times which is directly related to their travel times. Now the problem is to minimize the total passenger waiting times under the conditions of random passenger arrival, vehicle travel times, and vehicle arrival times. The  $ATT$  of the proposed model can be written as:

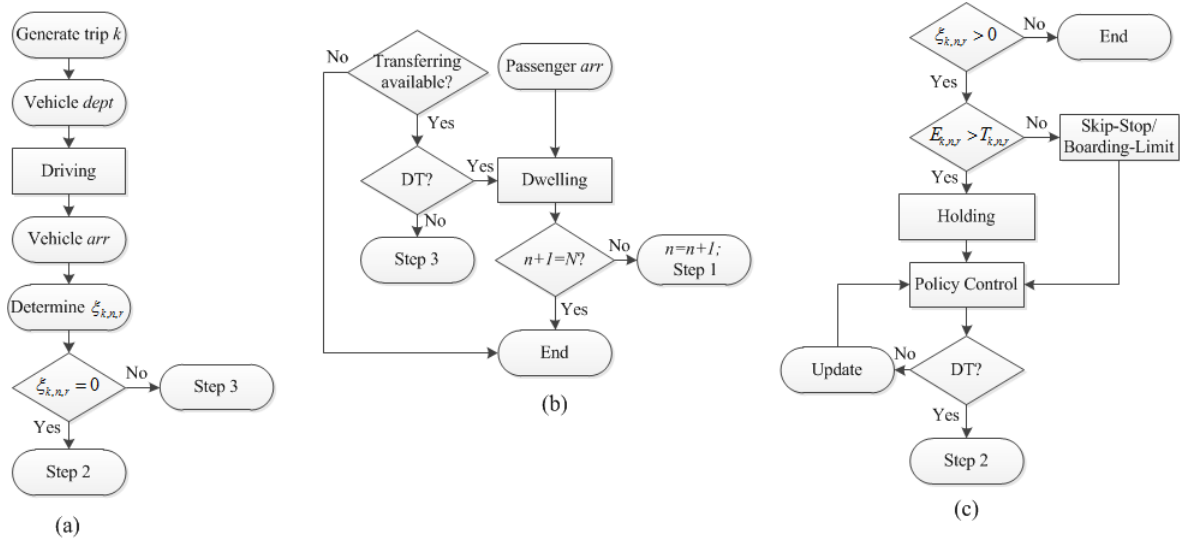
$$ATT = \min \sum_k \sum_n \sum_r \left( W_{k,n,r}^{stop} + W_{k,n,r}^{misses} + W_{k,n,r}^{in-vehicle} + W_{k,n,r}^{extra} + W_{k,n,r}^{skipped} \right) \quad (6.25)$$

### 6.3.8 Problem Assumptions

- (i) The vehicles are operated in FIFO manner, with an evenly scheduled headway per route.
- (ii) Route information, including, travel time distribution between stops, passenger arrival rates at each stop, and the distribution of transferring passengers are assumed known and fixed over the period concerned.
- (iii) Passengers aboard a vehicle will be informed of any action at the time of the decision so that they can choose to alight before or after the action.
- (iv) The PT drivers comply with the operational tactics instructions provided by their communication coordinator.
- (v) If there are passengers who want to disembark from the vehicle at a stop, then the vehicle cannot skip the stops.

## 6.4 Simulation Analysis

The evaluation of the performance under real-time operational tactics can be estimated with a PT system simulation model. The simulation model is discrete and not continuous. The simulation model adopts input and parameters from real-life data so that the performance of various control policies can be assessed under stochastic conditions.



**Figure 6.2:** Flowcharts of EA simulation process: (a) Step 1, (b) Step 2, and (c) Step 3.

#### 6.4.1 Event-Activity Process Modelling

The simulation is an event-based activity (EA) simulation. In the EA, the system changes its state as events occur. Activities are undertaken to achieve a specified outcome or a service. They have a duration and usually involve the use of process elements and resources (Kelton and Law, 2000). Two events are defined to describe the possible status of the vehicle: (i) departure of a vehicle from a stop (departure event), and (ii) arrival of a vehicle at a stop (arrival event). Two activities are also defined to depict the process of a PT service on the model: (i) traveling on the route between consecutive stops (driving activity), (ii) serving passengers at a stop (dwelling activity). Transferring is considered a part of dwelling activity at a transfer point in which missed transfers should wait for the next vehicle. Each event is triggered every time a vehicle reaches a stop. Vehicle loads, travel times, and position, as well as the number of passengers waiting at each stop and transferring passengers are updated in each event. The operational tactic deployment process then can be divided into sequence of decision stages based on events, minimize the gaps between the planned and actual headway, and minimize the additional total passenger travel time. In this way the implementation of operational tactics assists in reducing not only headway variation, but also in increasing the likelihood of direct transfers. A representation of the corresponding EA simulation process is shown in Figure 6.2.

### 6.4.2 Simulation Environment

The simulation software ExtendSim8 (ExtendSim, 2008), has been used to simulate the network. In the simulation, passengers arrive randomly following a Poisson distribution with mean  $\lambda_{n,r}$  at each stop. This distribution is common in service with headways of less than 12 min (Jolliffe and Hutchinson, 1975, Okrent, 1974). The boarding process follows a FIFO discipline. Thus, the earliest arriving passenger will be the first to board a vehicle if there is available capacity or will have to wait for the next vehicle if unavailable. The simulation model considers the vehicle travel times between two adjacent stops as a random variable with a log-normal distribution;  $LN(\mu, \sigma^2)$  that has been commonly used in previous studies (Andersson et al., 1979, Hickman, 2001). In the dwelling process, boarding and alighting take place at different doors. In the simulation, each passenger contributes the same marginal times when boarding and when alighting. The total dwell time is then estimated as the maximum time between these two processes.

## 6.5 Case Study

The proposed model for real-time tactics deployment was applied to examine real-life bus routes in Auckland, New Zealand. A case study for the Auckland region was based on AT (Auckland Transport) data, which consisted of the PT network, AT- HOP cards (Auckland Integrated Fares System), and a PT demand forecast. All buses of the Auckland transport network are equipped with AVL and GPS systems. These data are used to analyze bus travel times and headway adherence (to implement operational tactics). This means that real-time information on bus locations can be used to predict bus arrivals at the transfer points and to determine bus headway deviations. Analysis was carried out on three bus routes and two transfer points. The first route, known as Northern Express (NEX), has a dedicated lane that runs from the suburbs to and across the Auckland CBD area. It transports a very large number of passengers during peak hours and serves 10 stops. The second route, Route 858, runs north-south (east of the first route), and serves 63 stops; and the third route, Route 880, is a loop that serves as a feeder route with 62 stops. Routes 880 and 858 intersect at transfer point one on Bute Road, Browns Bay. Routes NEX and 880 connect at transfer point two at the Constellation Bus Station, Albany.

### 6.5.1 Control Policy and Scenarios

We tested and compared three different control policies. The first policy, No-Tactics, was used for comparison purposes. That is, the vehicles are dispatched from the terminal at a designed headway, without taking any control action along the route. By this policy, because of headway variation, direct transfers occurred infrequently. The second was the combination of Holding and Boarding-Limit policies. The last was the combination of Holding and Skip-Stop policies. In order to increase the likelihood of direct transfers, for both TBC policies, the rate of changes in Equation 6.14 was monitored and recorded at different locations before the transfer points. This enables investigation of the probability of vehicles meeting at transfer points. As summarized in Table 6.1, two scenarios were tested to evaluate and compare the proposed model under different operational conditions. These scenarios differ in service headways, which can be high frequency services (i.e., short headways), or medium frequency services. Average number of passengers per cycle time for the three routes (NEX, 858, 880) are, 312, 1252, and 951, respectively, and average number of transferring passengers is 18 passengers for two transfer points.

**Table 6.1:** Simulation scenarios

Scenario	Frequency	Route- headway (min)		
		R1(NEX)	R2(858)	R3(880)
1	High	5	7	5
2	Medium	10	12	10

### 6.5.2 Simulation Analysis

The proposed model was applied to the case study. Boarding and alighting times per passenger were set at 2.5 and 1.5 seconds, respectively. Vehicle capacity was given as 60 passengers, with 40 seated and 20 standing. Furthermore, vehicle headways, vehicle travel time distribution between stops, and passenger arrival time distribution are set per route. For every combination of policies and scenarios, 20 simulation runs were carried out, each of them representing four hours of bus operations. The maximum hold time used in all scenarios was 180 seconds, subject to the length of headways, and the average hold time was 39 seconds. The minimum and maximum headway variations, as the boundary for triggering an intervention were set to  $\pm 20\%$ .

## 6.6 Analysis of Results

The performance of the Auckland system was evaluated by means of total passengers waiting time. System reliability is represented by headway variance, which is calculated across all vehicle trips and stops, undoubtedly lower headway variance results in lower passenger wait times and indicates greater system reliability. Subsequently, for each scenario, four performance measures are used in comparing all policies: total waiting time for passengers; average cycle time, headway variation and the percentage of *DT*. The efficiency of the system was evaluated by means of control strength for different reduction levels. Thus, the best control strengths, as shown in Table 6.2, were set to earliness  $\alpha$ , and tardiness  $\beta$ , considering the greater reduction in total waiting times for passengers.

**Table 6.2:** Summary of the results

Scenario	Policy	Control strength	Total waiting time(s)	Avg. cycle time (s)	CV(h)	DT(%)	
						Simulation	Improvement
1	None	-	9156.87	7565	0.63	26.58	-
	H-BL	$\alpha = 0.75$ $\beta = 0.75$	3251.94	6859	0.25	55.6	115.50
	H-SS	$\alpha = 0.75$ $\beta = 1$	3543.53	6881	0.27	58.2	125.58
2	None	-	11368.62	7740	0.68	24.18	-
	H-BL	$\alpha = 0.75$ $\beta = 0.5$	4698.65	7092.4	0.28	57.9	140.25
	H-SS	$\alpha = 0.75$ $\beta = 1$	4358.36	6923	0.24	59.3	146.06

Note: H= holding; BL= boarding-limit; SS= skip-stops; CV= coefficient of variation; DT= direct transfer.

From Table 6.2, it is possible to draw an immediate conclusion that applying the combination of selected tactics improved overall system performance. Interestingly, with this control policy, not only are the expected total waiting times reduced (on average by 61%) in comparison with a no-control policy, but it also outperforms other control schemes in terms of reliability in meeting vehicles at transfer points. Thus, the tactics policies lead to an increase in direct transfers of up to 146% on the average for all scenarios. The findings also revealed that the use of tactics in the headway-based model does improve the system cycle time and presents the lowest cycle time (on the average by 9.3%) over the no-tactics policy. The reduction of cycle time, from the operator's

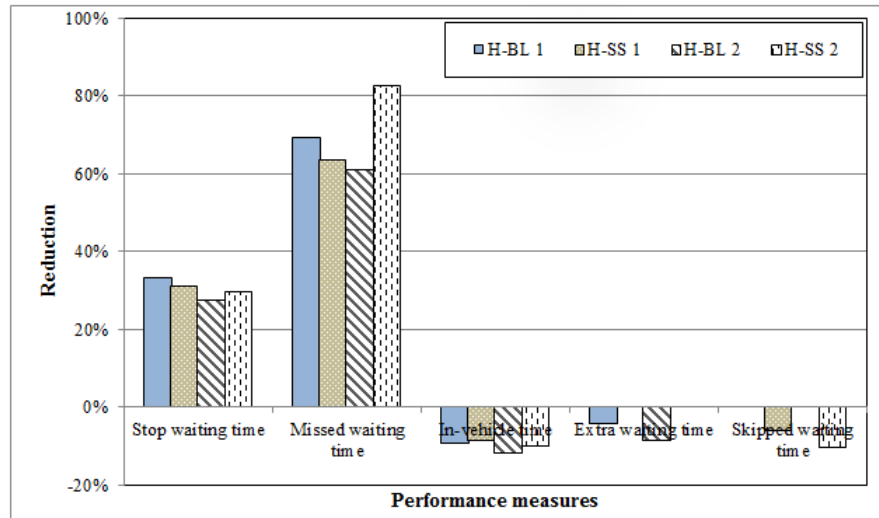
perspective, can potentially improve the fleet management to provide a given frequency. As Table 6.2 shows, the substantial reductions in the coefficient of variation of headways are achieved by the TBC policies. That is, the coefficient of variation of headways was less than 0.3 when utilizing tactics. This indicates that regular service results in shorter passenger waiting times and increases the direct transfers.

In the high frequency scenario, the results show a somewhat superior outcome for the holding and boarding-limit policy than for holding and skip-stops. However, the findings show that the holding and skip-stops policy for a medium frequency results in better performance than the holding and boarding-limit policy. This indicates that applying an appropriate combination of tactics in the related scenarios leads to considerable progress in PT service.

### 6.6.1 Control Effectiveness

Control effectiveness was compared in terms of reduced passenger waiting time. Identifying and understanding the effects and attributes of the model on passenger waiting time helps to ensure appropriate control strategies. This can be observed graphically in Figure 6.3, which illustrates the effect of the model on the average stop waiting time, missed waiting time, in-vehicle time, extra waiting time, and skipped waiting time with both scenarios. The result shows the greatest reduction in stop waiting time, 33.4%, is achieved by boarding-limit policy when the system is operating in the high frequency scenario. On the other hand, this policy resulted in significant increases in in-vehicle time, by 11.87%, in the medium frequency scenario.

It may also be observed from Figure 6.3 that with a medium frequency, holding and skip-stops policy contributes to a higher percentage of direct transfers. That is, the maximum number of direct transfers, using tactics, coincides with the minimum missed time. Again, the finding is consistent with the previous section that holding and boarding-limit policy, and holding and skip stops policy, yielded better performance in high and medium frequencies, respectively.



**Figure 6.3:** Tactics effectiveness with two scenarios.

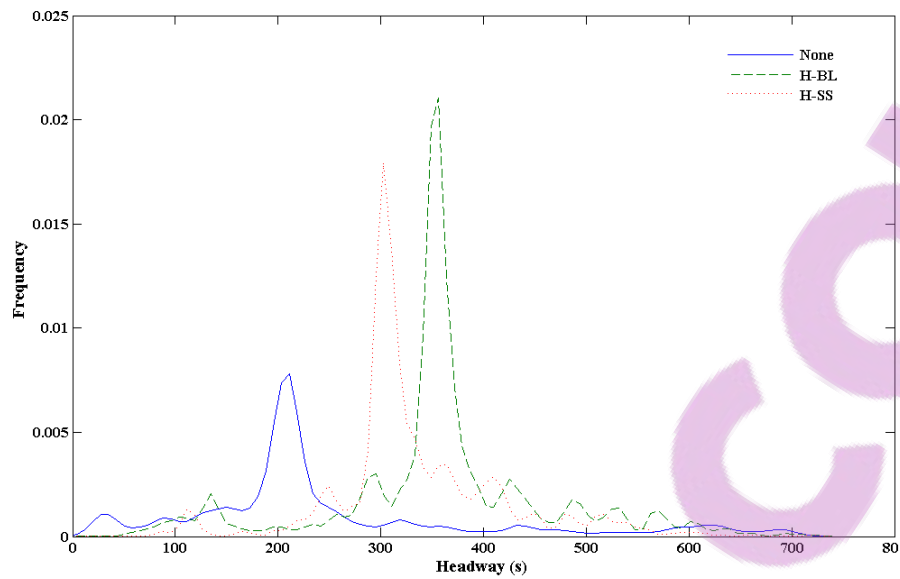
### 6.6.2 Headway Distribution

In addition to the evaluation of total waiting times for different scenarios, it is also possible to monitor the headway variation for a typical simulation run. The headway irregularity may result in increased passenger waiting time and lead to missed transfers. The simulation results illustrate the headway frequency distribution, over hours of the day and stops along a route. Figure 6.4 shows an example of headway distribution before and after applying the tactics. Route 880 is selected because this route is the feeder route of the case study and has two transfer points at stops 20 and 39, which allows for investigating direct transferring that appears with five-minute headway. The distributions are composed of all the headways between successive buses at all stops. For the TBC policies, the model shows close density for planned headway compared with no-tactic policy. Accordingly, Figure 6.4 shows that holding and boarding-limit policy yielded more regular service with a close headway distribution than for planned headway by a coefficient variation of 0.28.

## 6.7 Conclusions

A new real-time tactic-based control (TBC) procedure to increase the service reliability and actual occurrence of synchronized transfers in headway-based PT system has been developed. The procedure aims at minimizing additional travel time for passengers and





**Figure 6.4:** Headway distribution of Route 880, under various control policies.

reducing the uncertainty of meetings between PT vehicles. This work examined three control policies: no-tactics, holding and boarding-limit, and holding and skip-stops under two scenarios: high frequency and medium frequency services. The following general conclusions have been obtained from the simulation results:

- If possible, a combination of tactics should be applied to attain a considerable reduction in additional passenger travel time, and to outperform reliability in meeting vehicles at transfer points. Holding tactic for earliness, boarding-limit or skip-stops tactics for tardiness are quite beneficial with respect to control effectiveness.
- The presented headway based control model shows significant benefits in relation to the holding and boarding-limit, and holding and skip-stops over no-control policy in both scenarios.
- Compared with a no-control situation, the control policy presented shows that not only the expected additional total travel time is reduced (on average by 61%), but it also outperforms other control schemes in terms of reliability in meeting vehicles at transfer points. Thus, the TBC procedure leads to an increase in direct transfers of up to 146% on the average for all scenarios.

- In addition, the results demonstrate that holding and boarding-limit policy in high frequency service yield the better result. On the other hand, holding and skip-stops policy exhibit better performance in medium frequency service.
- A considerable improvement in direct transfers is attained in holding and skip-stop control policy. This indicates that this control policy is fairly robust to increase the likelihood of direct transfers.

Finally, the assessment of the framework presented in real life implementation would be based on advanced communication technologies, AVL, and automatic passenger count data. Future research, on which the authors have already been working, includes validation of some of the assumptions made, new control measures to develop the library of operational tactics, especially with the advancement of current technologies, the utilization of sensitivity analysis of different tactics, the introduction of a decision-support tool to provide information before implementing any control actions (controlling demand side), and evaluating the quality of the framework presented in a simulation model for more complex PT networks with different transfer types.

The effect of using the library of tactics in reducing the undesirable environmental impact is investigated in the next chapter.



## Chapter 7

# Energy Efficiency of Public Transport Systems Using Real-Time Control Method

*Submitted to:*

*Transportation Research Part D: Transport and Environment* (under review).

(Nesheli et al., 2015d)

### 7.1 Abstract

Public Transport (PT) systems rely more and more on online information extracted from both operator's intelligent equipment and user's smartphone applications. This allows for a better fit between supply and demand of the multimodal PT system, especially through the use of PT real-time control actions/tactics. In doing so there is also an opportunity to consider environmental-related issues to approach energy saving and reduced pollution. This study investigates and analyses the benefits of using real-time PT operational tactics in reducing the undesirable environmental impacts. A tactic-based control (TBC) optimization model is used to minimize total passenger travel time and maximize direct transfers (without waiting). The model consists of a control policy built upon a combination of three tactics: holding, skip-stops, and boarding limit. The environmental-related measure is the global warming potential (GWP) using the life

cycle assessment technique. The methodology developed is applied to a real life case study in Auckland, New Zealand. Results show that TBC could reduce the GWP by means of reduction of total passenger travel times and vehicle travel cycle time. That is, the TBC model results in a 5.6% reduction in total GWP per day compared with an existing no-tactic scenario. This study supports the use of real-time control actions to maintain a reliable PT service, reducing greenhouse gas emissions and subsequently moving towards greener PT systems.

## 7.2 Introduction

On the global scale, transport activity for both passengers and freight is growing rapidly and is expected to double by 2050 (IEA, 2009). Internationally, increased attention has been directed towards green transportation as governments are faced with the onset of climate change. The environmental impacts of transportation systems are considerable, accounting for 20% to 25% of the world's energy consumption yearly (Zhou et al., 2010). Energy use in the transportation sector (i.e., gasoline, diesel, or liquefied petroleum gas, with most vehicles being operated with gasoline or diesel), has made a major contribution to the deterioration of urban air quality and is responsible for a significant amount of greenhouse gas (GHG) emissions, which include: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), chlorofluorocarbons (CFCs), and sulfur hexafluoride (SF<sub>6</sub>).

The rise in transport use of energy has resulted primarily from increased use of the private car for personal transport (Potter, 2003). Technological developments such as fuel-efficient vehicles and alternative energy sources provide a means to address this concern, though current efforts fall short of counterbalancing the impacts of this growth (Rode and Burdett, 2011). Therefore, it is desirable to provide travelers with a viable alternative to private cars. Undoubtedly, the use of public transport (PT), being accountable for only a fraction of the total emissions, can help make transportation more economical and efficient in terms of use of resources (Hassold and Ceder, 2014). However, in terms of reliability, efficiency, and environmental impacts, PT itself has great potential for improvement (Beirão and Cabral, 2007, Hassold and Ceder, 2014, Keirstead et al., 2012, Kimball et al., 2013, Nesheli and Ceder, 2014).

Due to the fact that most PT attributes (travel time, dwell time, demand, etc.) are stochastic, the passenger is likely to experience unplanned waiting and trip times. This uncertainty (especially for buses) will create the undesirable vehicle-bunching phenomenon, unproductive service, increase of passenger waiting and travel times, and of passenger frustration. Inefficient PT operation not only causes a loss of existing and potential passengers, but also leads to major detrimental impacts on environmental aspects and resources. Principally, one of the most challenging problems of transportation planning is how to shift a significant amount of car users (who consume the highest percentages of the energy used for transportation) to PT in a sustainable manner. Findings show that in order to increase PT usage, the service should be considered in a way that provides the levels of service required by passengers and by doing so, attract potential users (Beirão and Cabral, 2007). Following Hanaoka and Qadir, the need to attract people from personal automobiles to PT is vital for achieving a sustainable transport system (Hanaoka and Qadir, 2009). Levinson demonstrates that a reliable transit service is essential for attracting and retaining riders, principally in modern societies, which make many transportation options (Levinson, 2005) available. As shown in Ceder, an attractive, advanced PT system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, constitutes part of the door-to-door passenger chain (Ceder, 2007, 2015).

A vast amount of research has been conducted on how to optimally or efficiently utilize the PT system. One efficient approach to alleviating the uncertainty of the PT service, such as simultaneous arrival of vehicles at a transfer point, and rectifying the service irregularity is to use real-time operational control actions (tactics), like holding, skip-stop, and short-turn. Daganzo showed that without interventions (i.e., control actions), bus bunching was almost inevitable regardless of the driver's or the passengers' behavior (Daganzo, 2009). With regard to transfer reliability, some recent studies show that applying certain operational tactics can significantly increase the number of direct (simultaneous) transfers and reduce total passenger travel time (Hadas and Ceder, 2010a, Liu et al., 2014, Nesheli and Ceder, 2014, 2015b).

With respect to using the intelligent transportation system (ITS) and environmental impacts, the European Commission published a comprehensive qualitative analysis of the potential of ITS technologies for reducing greenhouse gas emissions related to road transport and suggests that more research on the energy-reducing capacity of ITS

applications is required (Bani et al., 2009). Dessouky et al. (1999) show the potential benefits of real-time control of timed transfers using intelligent transportation systems (ITS). The results showed that advanced technologies were most advantageous when there were many connecting buses - the schedule slack was then close to zero.

In New Zealand, the transportation sector is responsible for producing more than 40% of the CO<sub>2</sub> emissions and it is the fastest growing source of greenhouse gas (GHG) emissions (Macbeth, 2004). A recent study shows that private vehicle transport in New Zealand is less energy-efficient and produces 65% of CO<sub>2</sub> emissions in comparison with 15.8% of CO<sub>2</sub> emissions from the whole PT sector (Ministry, 2013). The key findings of the Auckland Regional Council show that providing efficient PT system combined with some improvements to the road network will be a key element to limit growth in private care use and will be more effective in reducing growth in CO<sub>2</sub> emissions (AT, 2013). The Auckland Transport Regional Public Transport Plan (AT, 2013) was created for the purpose of developing an integrated transport network to provide Aucklanders with a sustainable transport system in a safe, integrated and affordable manner. This plan shows the intensive discussion conducted on various issues relating to PT systems of the future. Indeed, a major focus over the next decade will be on enhancing the PT system. Thus, there is need to investigate the performance of Auckland's PT system to meet sustainability goals.

Although extensive research has been conducted to analyze PT movements at control points, there has been no specific analytical study dealing with environmental impacts related to real-time control actions. There is a need, then, to assess the effect of applying real-time tactics on environmental factors. To date, life cycle assessment (LCA) tools have generally been used for knowledge generating studies either as standalone quantification tools or for comparisons of different alternatives. LCA studies of the environmental impacts of road vehicles showed that a running vehicle consumes 80%-90% of total life cycle energy use (IEA, 1993). This means that other stages of its life cycle, (i.e., production and processing of materials, vehicle manufacture, maintenance and disposal stages) are relatively insignificant compared to the energy consumed and emissions produced when vehicles are in use. The research is undertaken in two phases: (a) an assessment of the performance of the PT system before and after implementation of real-time control actions (tactics), (b) an evaluation of the environmental impacts of the PT system before

and after utilizing real-time control tactics. This study will provide PT agencies with evidence to support sustainable transportation and move towards a green PT system.

*Objective:* The objective is to develop an efficient and environmentally sustainable method for policymakers to operate PT networks through the use of operational tactics. The method enables agents to make PT systems greener and more reliable. This will certainly make the PT service more attractive, efficient, and thus, will encourage people to leave their car at home and use the PT service. To the authors' knowledge, the present study provides, for the first time in the literature, a description of environmental aspects of real-time control actions at the operational level.

The following section provides more information on the environmental impacts of PT systems. Afterward, the LCA framework and its definitions are described. The methods used for a process of real-time control actions to maintain the scheduled headway, and thus for achieving maximal transfer synchronization, are briefly presented before the introduction of a case study and associated results. Finally, the paper provides a discussion and conclusions, including an outlook on future research in this area.

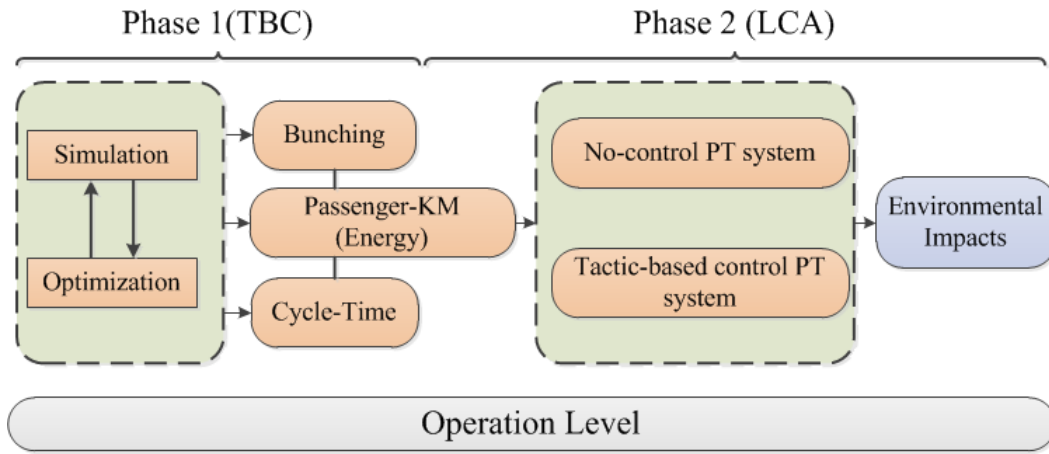
## 7.3 Methodology

To examine the potency of using a real-time control method for reducing environmental impacts we developed a two phase methodology: (1) constructing a real-time PT tactic-based control (TBC) system using three tactics: holding, skip-stops, and boarding limit, (2) designing a LCA process to evaluate the environmental impacts of the PT system before and after the operational use of TBC. The two phases are explicated as follows. Figure 7.1 shows the methodology.

### 7.3.1 Real-time Control System

According to the methodology introduced in Nesheli and Ceder (2014), a real-time control method is considered for the reduction of the uncertainty of a PT system. The objective is to minimize the total passenger travel time, TPTT, and in this way, to maximize the total number of direct transfers, DT. The minimization of TPTT and occurrence of DT ensures that the level of service is satisfactory and passengers do not have to endure unappealing





**Figure 7.1:** Overview of the methodology; Phase 1: Tactic-based control (TBC) and Phase 2: Life cycle assessment (LCA).

waiting times. Moreover it allows for efficient operation of the vehicles used by delivery of the regular service. The algorithm uses a real-time approach under simulation & optimization-based framework. The methodology commences by the use of the event-based simulation tool, ExtendSim (2008) to represent a real-life example and to generate random input data for the proposed optimization model. Then standard optimization software, ILOG (IBM, 2012), is used to optimally solve a range of different events determined by the simulation runs. Finally, more simulation runs are made, containing the tactics determined by the optimization program, so as to validate the results attained by the model. Therefore, a library of tactics can be constructed and applied in order to bring about system improvement. The formulation of the problem is given as follows:

**State Variables:**

$l_{n,r}$  Passenger load of route  $r$  at stop  $n$

$b_{n,r}$  The number of passengers boarding on route  $r$  at stop  $n$

$a_{n,r}$  The number of passengers alighting on route  $r$  at stop  $n$

$p_{n,rx}$  The number of passengers transferring from route  $r$  to route  $x$  at stop  $n$

$d_{n,r}$  Vehicle dwell time of route  $r$  at stop  $n$  (in seconds)

$H_r$  Vehicle headway of route  $r$

$m_r$  Maximum total number of stops of route  $r$

$T_r$  Vehicle schedule deviation of route  $r$

$\Omega_{n,r}$  Time penalty function of route  $r$  at stop  $n$

**Decision Variables:**

$HO_{n,r}$  Vehicle holding time of route  $r$  at stop  $n$

$S_{n,r}$  Vehicle skipping stop of route  $r$  at stop  $n$ ; if stop skipped= 1, otherwise= 0

$BL_{n,r}$  Vehicle boarding limit of route  $r$  at stop  $n$ ; if stop boarding limited= 1, otherwise= 0

$Y_{n,rx}$  Possible transferring from route  $r$  to route  $x$  at transfer stop  $n$ , pre-tactics; if a possible transfer occurs= 0, otherwise= 1

$Z_{n,rx}$  Possible transferring from route  $r$  to route  $x$  at transfer stop  $n$ , post-tactics; if a possible transfer occurs= 0, otherwise= 1.

### 7.3.2 Assumption

It is assumed that the vehicles are operated in FIFO manner, with an evenly scheduled headway per route. Route information, including travel time distribution between stops, estimation of passenger arrival rates at each stop, and average number of transferring passengers are assumed to be known and fixed over the period concerned. It is also assumed that passengers aboard a vehicle will be informed of any action at the time of the decision so that they can choose to alight before or after the action.

### 7.3.3 Optimization Problem Formulation

The problem is formulated as a mixed-integer programming (MIP) problem. Optimization programming language (OPL) using ILOG (IBM, 2012) allows us to execute the optimization problem to optimally solve the value of each decision variable. Each of the three waiting times associated with the tactics are weighted by  $\delta_1$ ,  $\delta_2$ , and  $\delta_3$ .

#### (a) Holding

The effect of holding tactic on the change in total passenger travel time with respect

to route  $r$  and stop  $n$  is:

$$\begin{aligned} \Delta TPTT(Holding)_{n,r} = & HO_{n,r} \left[ \delta_1(l_{n,r} + b_{n,r}) - a_{n,r} + \sum_{i=n+1}^{m_r} (b_{i,r} \right. \\ & \left. + \sum_{x \in R, x \neq r} (1 - Z_{i,xr}) p_{i,xr}) + \sum_{x \in R, x \neq r} ((1 - Y_{n,xr}) p_{n,xr} - p_{n,rx}) \right] \end{aligned} \quad (7.1)$$

**(b) Skip-stops**

Skip-stops encompasses both skip-stop and skip-segment tactics. Consequently the effect of the skip-stops tactic on the change of the total travel time for route  $r$  and stop  $n$  is:

$$\begin{aligned} \Delta TPTT(Skip - stops)_{n,r} = & S_{n,r} \left[ \delta_2 \left( a_{n,r} \Omega_{n,r} + b_{n,r} (H_r - T_r) \right) \right. \\ & \left. - d_{n,r} \left( l_{n,r} + \sum_{i=n+1}^{m_r} \left( b_{i,r} + \sum_{x \in R, x \neq r} (1 - Z_{i,xr}) p_{i,xr} \right) \right) \right] \end{aligned} \quad (7.2)$$

**(c) Boarding-limit**

Boarding-limit tactic can be a complementary control action for holding to further reduce headway variation when the demand and travel times vary randomly. Those advantaged by boarding-limit tactic are those who are currently on the vehicle and those who will board the vehicle in the future. The time saving for them is dwell time. The effect of boarding-limit tactic on the change in total passenger travel time with respect to route  $r$  and stop  $n$  is:

$$\begin{aligned} \Delta TPTT(Boarding - limit)_{n,r} = & BL_{n,r} \left[ \delta_3 \left( b_{n,r} (H_r - T_r) \right) \right. \\ & \left. - d_{n,r} \left( l_{n,r} + \sum_{i=n+1}^{m_r} \left( b_{i,r} + \sum_{x \in R, x \neq r} (1 - Z_{i,xr}) p_{i,xr} \right) \right) \right] \end{aligned} \quad (7.3)$$

**(d) Transfers**

It is possible to measure the effect of making or missing synchronized transfers on the change in total passenger travel time by the definition of direct transfers. Therefore, a direct transfer occurs if the following holds:

$$Y_{n,rx} + Y_{n,xr} = 0 \quad (7.4)$$

$$Z_{n,rx} + Z_{n,xr} = 0 \quad (7.5)$$

The real-time transfer problem is formulated as follows:

$$\Delta TPTT(Transfer)_{n,r} = \sum_{x \in R} \left[ p_{n,rx} (Z_{n,rx} - Y_{n,rx}) (H_x - T_r) \right] \quad (7.6)$$

(e) **Objective function**

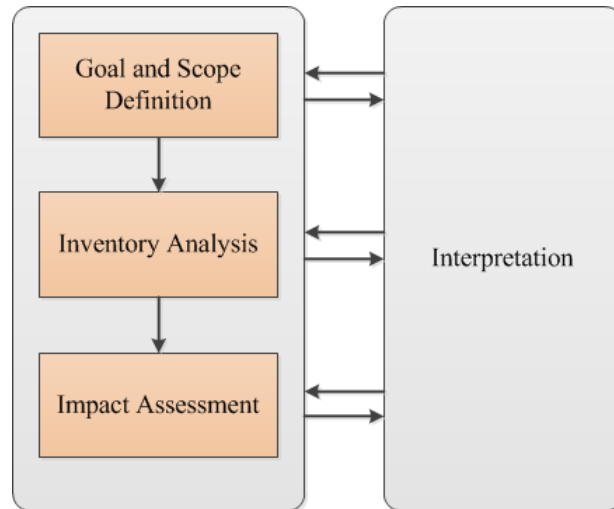
The objective function of the proposed model can be written as:

$$\begin{aligned} \min \sum_{n \in N} \sum_{r \in R} \Delta TPTT & \left( Holding_{n,r} + Skip - stops_{n,r} \right. \\ & \left. + Boarding - limit_{n,r} + Transfer_{n,r} \right) \end{aligned} \quad (7.7)$$

(f) **Constraints**

- The transfer points cannot be skipped.
- Tactics cannot be applied on stops that a vehicle is not going to or which have already passed.
- It is not allowed to skip the first stop.
- Skipping, boarding-limiting, and holding are not allowed at the same stop.
- The maximum holding time is not more than half the headway of the route.
- If a transfer occurs in the pre-tactics situation, the same apply to a with-tactics situation.
- If direct transferring is possible without the use of any tactic, there is no need to interfere.
- If the use of tactics does not result in a transfer, no tactics are applied.
- To restrict the number of passengers aboard (capacity-based) when the vehicle departs the stop, checking constraint is introduced.

With a set of optimal value tactics, the algorithm can not only reduce the passenger travel time, but also ensures that the direct transfer occurs with respect to the objective function. Effects on PT system efficiency and total energy use will be examined in the following section.



**Figure 7.2:** Life Cycle Assessment Framework.

### 7.3.4 Environmental Impact

LCA is a systematic process by which the energy requirements and environmental impacts of product systems are calculated from raw material acquisition to final disposal. Inputs and outputs are accounted for during various stages of a product's life cycle (ISO, 2006). A LCA is carried out based on two sets of standards - the ISO 14040: 2006 and ISO 14044:2006. This process consists of four main stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation (ISO, 2006). Figure 7.2 illustrates the statements.

The ISO 14040-series contains:

- 14040: Principals and framework;
- 14041: Goal, scope and inventory analysis;
- 14042: Impact assessment;
- 14043: Life cycle interpretation.

Life cycle inventory (LCI) is one element of LCA that deals with quantifying the inputs and outputs of other stages. Life cycle impact assessment (LCIA) is another stage that calculates the impact of inputs and outputs which are assigned to different environmental impact categories. The characterization factor is used to calculate the contribution of each

of the constituents for different environmental impact categories (climate change, ozone depletion, eco toxicity, human toxicity, photochemical ozone formation, acidification, eutrophication, resource depletion, and land use) (Cabeza et al., 2014).

The LCA software GaBi has been used to assess the environmental impacts. GaBi is a process-based model and software. It uses an integrated products database developed through industry reviews and technical literature (Eyerer, 2006). GaBi is implemented alongside CML 2001, an impact assessment methodology. CML is a problem-oriented approach that assesses inventory flows for the impact categories (GaBi, 2014).

### 7.3.5 LCA Framework

**Goal definition:** The main goal of the study is to identify key issues associated with the life cycle of the PT system operation process. The secondary goal is to provide policymakers and PT operators with suggestions on how to more efficiently operate PT systems for energy conservation, emission reduction, and sustainable development for the entire transportation sector. Following are the specific objectives:

- Determining the environmental implication of the PT system operation in conventional situation, no-control system, and TBC system.
- Analyzing and comparing the LCA environmental impacts of the two scenarios.

The first objective informs environmental design improvement initiatives by providing detailed information about the environmental impact of each model. The second objective was defined as a specific focus within the LCA study because TBC method is actively investigating the best operation strategy for PT.

**Scope:** The aim of the study consists of all possible processes from start gate to end gate during one working day of the PT system at the operation level within practical limitations. The inventory inputs and outputs of the service include the following stages:

- The system underlying the model is a transit network consisting of main and feeder routes. Transfers occur at separate transfer points for each route.
- A service is made up of a collection of trips. Each trip represents a single run, based on a certain departure time, along the series of stops on the route.

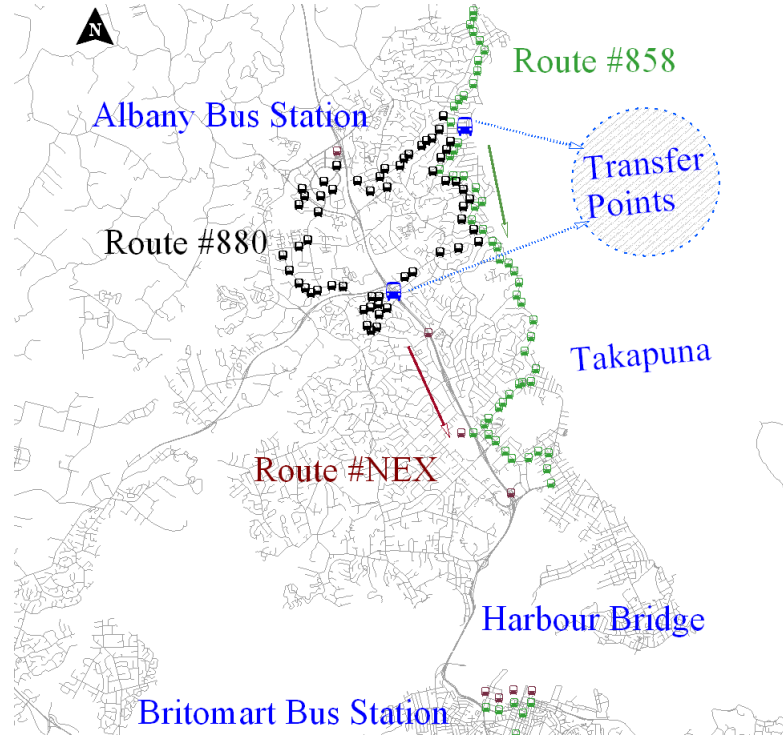
- In the network, passengers arrive at stops randomly (passenger/minutes).

In this paper, LCA is applied with restricted boundaries, such as assessing the operation of a single day, and thus, does not implement the full LCA cradle-to-grave methodology.

**Functional units, life cycle inventory impact assessment:** The functional unit of the PT system can be defined as passenger-kilometer. The inventory involves the type of bus driven, the consumption mix and the engine size using GaBi database (GaBi, 2014).

## 7.4 Case Study

The proposed method has been applied to a real-life case study from Auckland, New Zealand. Data are based on an existing bus network in one section of Auckland. Buses accounted for 76% of all PT boardings in Auckland in 2012 (Balcombe et al., 2004). As Figure 7.3 illustrates, the selected network consists of three bus routes and two transfer points. The first route with a dedicated lane runs from the suburb across the CBD area and has quite a high number of passengers during peak hours. The second route runs north-south (east of the first route), and the third route is a loop that serves as a feeder route. Running times and passenger loading data are based on smartcard transactions. This method provides rather accurate information about ridership and transferring passengers. Data errors and missing information, (i.e., card-reading errors and cash paying passengers), are controlled in a way that tends to overestimate ridership. That is, cash-paying passengers or passengers failing to swipe their card when alighting are assumed to travel the maximum distance and get off at the final stop. In the dwelling process, boarding and alighting take place at different doors. In the simulation, each passenger contributes the same marginal time when boarding and when alighting. The total dwell time is then estimated as the maximum time between these two processes. Boarding and alighting times per passenger were set at 2.5 and 1.5 seconds, respectively. Vehicle capacity was given as 60 passengers, with 40 seated and 20 standing. The vehicle speeds at which the buses travel at are limited to the class of the road, CBD or non-CBD, and the time period - peak or non-peak hours. In this study, on the average, the bus speeds in the CBD are 16kph, and 45kph in non-CBD.



**Figure 7.3:** Bus system and the study routes, Auckland, New Zealand.

The case examines the data for a whole day with 16 hours of service. Two cases have been examined: one with no-tactics control policy, and the other with the combination of three real-time, tactic-based control policies modelled. To establish comparability of the two scenarios, it is assumed that the PT network was synchronized (at the planning stage). The objective of the optimization process was to attain a better synchronization, considering the changes in travel times that might result from traffic congestion or changes in passenger demand for operation level.

## 7.5 Analysis and Results

### 7.5.1 Analysis of TBC Model

The performance of the case study was evaluated by means of total passenger travel time, missed transfers, average cycle time and the percentage of bus bunching occurring. The PT network has been simulated for handling the concept of synchronized transfers and generating input data for optimization. The mathematical formulation was coded in OPL using ILOG (IBM, 2012) and implemented on an Intel Core<sup>TM</sup> i5 – 2500 CPU



@ 3.30 GHZ and 8.00 GB RAM. The execution time of the procedure varies from 7-12 seconds for a proposed PT system model with 133 stops in the Auckland data. Such a small computation time clearly meets the needs of a real-time control system. Results of the system performance for both scenarios are shown in Table 7.1.

**Table 7.1:** PT system performance

Policy	TPTT (passenger-kilometer)	Missed transfer (passenger-minutes)	Avg. cycle time (minutes)	Bunching (%)
None	341,770.70	23111	166.9	32.4
TBC	322,634.91	1337	145.5	8.1

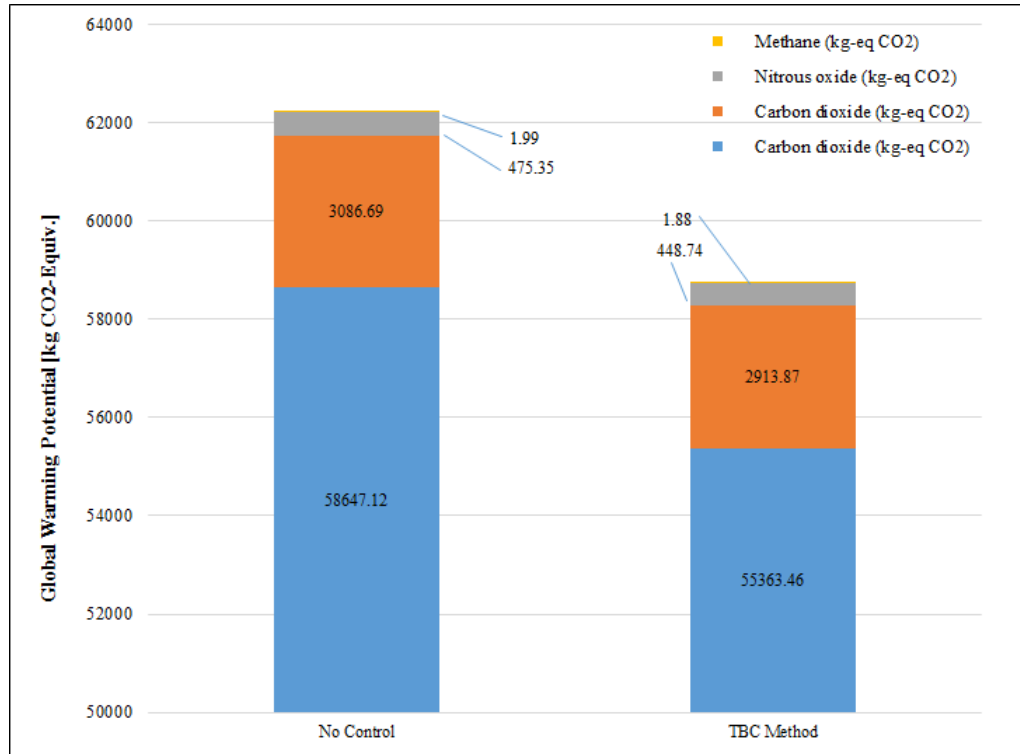
Note: TBC= holding, boarding-limit, skip-stops

**Total passenger travel time:** The effect of the TBC method on the change in the total passenger travel time indicates that an efficient PT system will save passengers travel time and lead to energy saving. The results revealed that the TBC process does improve system performance considerably, by 5.6%.

**Missed transfer:** Missed transfer is one of the undesirable features of the PT service and increases frustration of passengers. Missed connections of a transfer service will not only dissatisfy current passengers, but also a cause of discouragement for potential new users. Thus, this unreliability results in a decreased number of PT users or shifting to private cars, whereas the smaller passenger occupancy of vehicles leads to an increase in the environmental impacts. The finding shows that by applying TBC method, missed transfers can be decreased by 94%.

**Average cycle time:** Obviously reducing vehicle kilometers travelled leads to reducing total energy consumption. The findings indicate that TBC method improves average cycle times by 13%.

**Bunching:** Vehicle bunching takes place when headways between vehicles are irregular. The bunching indicates that the bunched buses may result in empty seat trips and increase inefficient operation for the individual vehicles. Bunching ultimately leads to an increase in total fuel consumption. The results of the case study show that using TBC method with the real-time control actions can reduce the bunching of the vehicles by 75%.



**Figure 7.4:** Global warming potential of no control and TBC method.

### 7.5.2 Analysis of Environmental Impacts

The main results of the environmental impacts of both cases are summarized in Figure 7.4. The transport process is computed by means of the GaBi dataset and a revised version of the CML2001 dataset method (2013 version) (GaBi, 2014). For this study, the Scania K320, and ADL - E200, which are used in the Auckland PT system, have been selected. These buses are considered environmentally friendly with a Euro 5+ emissions standard. The functional unit of an operation system is passenger-km that is identified as a kilometer distance where one passenger moves it. The inventory-vehicle diesel Euro 5, passenger car, consumption mix, engine size more than 2L is chosen for life cycle inventory from GaBi database (GaBi, 2014). Impact assessment was carried out by using GaBi LCA software, employing CML2001 methodology. For the purpose of this paper, only characterization results for global warming potential (GWP100) are presented. This category was chosen for two reasons: (1) global warming is a significant issue for businesses and the environment, and (2) other categories follow a similar pattern of results to that of the GWP100 category.

## 7.6 Conclusion

Within this paper we analyze the benefits of implementing a real-time operational tactic scheme for the purpose of reducing the environmental impacts of PT systems. Accompanying the methodological development, we present a case study for Auckland, New Zealand using a local bus transportation network.

Reductions in TPTT, missed transfers, average cycle time, and bunching highlight the efficiency improvements that can be achieved for the local transportation system when using real-time operational tactic control. In addition to improving energy efficiency, it is taken into consideration that minimizing these PT factors will improve customer satisfaction, helping to retain and even attract passengers away from heavily polluting private transportation (cars) towards more energy-efficient PT systems. Using LCA, we show that by applying the TBC model a 5.6% reduction in total GWP per day is attained compared with the no-tactic scenario.

The methodology introduced in this paper has a wide range of applications for PT systems in different geographic settings. Extensions of the work include: (i) Implementation of the LCA methodology to evaluate other environmental factors, including: acidification, eutrophication, and ozone-depletion; (ii) Extension of the methodology to evaluate the implications of real-time control savings on a multimodal transport system; (iii) The development of methodology and analyses to evaluate the full environmental and cost benefits of retrofitting local bus services with control systems for applying TBC.

In implementing this study we make use of the GaBi database which contains datasets understood to be limited in scope. (For example, they do not contain the exact bus characteristics as they are operated in the city of Auckland.) Thus, in developing this study we have made a number of assumptions regarding vehicle types. Other assumptions have been highlighted for the TBC scheme. Despite these limitations, we believe that this study makes a valuable contribution, not only in terms of the integration of PT control methodology with the LCA approach, but also by demonstration with real-world operational data.

This study provides evidence to support the use of real-time control actions to maintain a reliable PT service, reducing greenhouse gas emissions, and subsequently moving towards greener PT systems. Given these benefits, there is real potential for the

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TBC model to be deployed in real life, providing a major advantage for PT operators, policymakers and PT users.

The next chapter investigates the effect of implementing real-time tactics on passengers' perceptions and decisions (the demand side) as complementary to the operational side (i.e., [Chapters 2-6](#))

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## Chapter 8

# Matching Public Transport Demand Using Tactic-Based Guidelines

*Submitted to:*

*Transport Policy* (under review, 2<sup>nd</sup> round).

(Nesheli et al., 2015c)

### 8.1 Abstract

An important step in the development of an integrated system is for policy-makers and public transport (PT) operators to remove the uncertainty of PT service performance in real-time. Implementing proper control actions, such as tactics, leads to reducing passenger waiting time and preventing missed transfers. These two undesirable features are major contributors to PT's negative image. However, there has been no specific investigation of the effect of implementing tactics on passengers' perceptions and decisions (demand side). This paper presents the results of a qualitative and quantitative study of PT users to obtain a deeper understanding of travelers' attitudes toward transport uncertainty and to explore perceptions of real-time operational tactics on PT service quality. The study is undertaken in two-parts: (a) assessment of the effects of delay on PT users' perception and decision to change route or mode; (b) evaluation of users' decision

based on various real-time operational tactics. To investigate users' perception and decisions related to various operational tactics, a user-preference survey was conducted at a major terminal in Auckland, New Zealand, and Lyon, France. The survey data was modeled following a Multinomial Logistic Regression and a decision-tree-based method. The statistical analysis emphasized that, in various situations (e.g., waiting at a stop for more than 10 minutes), more than 60% of the travelers will change their decision and adapt travel behaviors based on a decision-support tool. The findings provide policy makers with an understanding of the behavioral aspect of real-time operational tactics.

## 8.2 Introduction

The need to attract people from personal automobiles to public transport (PT) is paramount for achieving a sustainable transport system (Hanaoka and Qadir, 2009). PT agencies have adopted a common tactic of developing an integrated, effective multi-modal transport system in order to provide travelers with a reliable alternative to private cars. Improving PT service reliability is one of the most important tasks in PT planning and operations. Unreliable PT services have been found to be one of the main reasons for the considerable reduction in PT service attractiveness (Ceder, 2007, 2015). As a result, continued unreliable PT service will not only frustrate existing passengers, but will also cause the loss of potential new users. Ceder (2007, 2015) showed that attractive, advanced PT was a system that operated reliably and relatively rapidly, with smooth (ease of) synchronized transfers and constituted part of the door-to-door passenger chain. Levinson (2005) demonstrates that reliable transit service is essential to attracting and retaining riders, principally in modern societies, where many transportation options are available.

Balcombe et al. (2004), in a practical UK transit guide, reported that in passengers' perception, the reliability of local bus services is considered twice as important as the element of frequency. Because of some uncertain and unexpected factors, such as traffic disturbances and disruptions, inaccurate PT-driver behavior and actions, and random passenger demands, a pre-planned, scheduled PT service does not always materialize, especially synchronized-transfer service. Iseki and Taylor (2009) argued that PT users' perceived waiting time has been shown to be more onerous than the actual waiting time and is dependent on waiting conditions, such as personal safety, connection reliability,

and comfort. Vincent (2008) showed that transit passengers perceive unexpected waiting time to be 3 to 5 times more burdensome relative to in-vehicle time. A recent study by Ceder et al. (2013a) investigated the effects of uncertainty in out-of-vehicle times during transfers on PT users' willingness to use transfer routes. Their findings show that increasing consistency in out-of-vehicle times will increase the attractiveness of transfer routes, thus enabling a more efficient, integrated network of PT routes to result in the enlargement of ridership. One efficient approach to alleviate the uncertainty of the simultaneous arrival of vehicles at a transfer point and to correct schedule deviations is to use selected operational tactics, such as holding, skip-stop, and short-turn. Studies (Ceder et al., 2013b, Hadas and Ceder, 2010a, Nesheli and Ceder, 2014) show that applying certain operational tactics can significantly increase the number of direct (simultaneous) transfers and reduce total passenger travel time.

Hanaoka and Qadir (2009) investigated bus passengers' behavior and perceptions of the use of potential features of an automatic vehicle-location (AVL) system in bus transit. The study involved an attitudinal on-board survey to understand respondents' behaviors in Bangkok. The work focused on measuring the effects of a bus-holding strategy using AVL technology in bus operation utilizing a simulation model. Concerning passengers' information systems, Eboli and Mazzulla (2012) argued that a high-quality information system was an essential factor in retaining existing riders and attracting potential users and thus increase ridership. Studies (Bachok, 2007, Grotenhuis et al., 2007, Molin et al., 2009) have shown that integrated information systems are required to facilitate transfers between urban and interurban multimodal PT networks.

A recent study by the authors (Nesheli and Ceder, 2014) investigated how selected operational tactics should be used in PT networks to increase the actual occurrence of scheduled transfers. Their model determined the impact of instructing vehicles either to hold at or to skip certain stops/segments on total passenger travel time and the number of simultaneous transfers. Although extensive research has been conducted to analyze PT movements at control points, there has been no specific analytical study dealing with passengers' perceptions and decisions related to real-time control actions. There is need, then, to assess the effect of applying real-time tactics in a proper study of demand side perceptions and decisions as complementary to the agent side. The expected contribution of the present study is to provide PT agencies with a perception of demand control. The research is undertaken in two-stages: (1) an assessment of the effects of delay on



PT users' perception and decision to change route or mode; (2) an evaluation of users' decisions based on various real-time operational tactics.

The objective is to develop a real-time guideline for both policy-makers and passengers in terms of using possible operational tactics in order for users to make the best possible decision in any uncertain event. The PT agents can provide PT users with different possible options, including operational tactics, with real-time information. Passengers can thus make a decision based on the available options. The method enables agents to control demand, redirecting and allocating passenger flows.

The primary aim of this study is to collect and analyze information on PT passengers' behaviors and their perceptions related to the use of potential features of a decision-support tool in the existing PT system. A secondary aim is to determine the potential benefits of a control strategy using selected operational tactics to reduce the uncertainty of passengers' travel-times by increasing PT service reliability. The specific objectives to achieve the study's aims are as follows:

- To assess PT passengers' perceptions and expectations of the potential features of a decision-support tool.
- To determine and compare passengers' decisions modeled in different scenarios.
- To determine the effect of implementing selected operational tactics on passengers' decisions.
- To assess the importance of PT service factors in passengers' preferences.

To the authors' knowledge, the present study provides, for the first time in the literature, a description of two commonly used models: Multinomial Logistic Regression (MLR) and a Decision Tree (DT)-based method for passengers' decisions, CHAID. Section 8.3 of this work presents the research methodology, Section 8.4 describes the two modeling procedures and results, Section 8.5 provides a tolerated time model and a discussion of the use of the application and operational tactics, and Section 8.6 presents the conclusions and recommendations for future study.

### 8.3 STAGE 1: Methodology and Findings of Users' Perception of The Service Factor

Because of the complexity of travel behavior, a deeper understanding of people's perceptions, attitudes, and behavior is required (Beirão and Cabral, 2007). Qualitative and quantitative methods can be used to explore this complexity. Quantitative approaches have the advantage of measuring the reactions of many subjects by a limited set of questions, thus allowing the comparison and statistical aggregation of the data. Qualitative methods produce a wealth of detailed information on a small number of individuals (Patton, 1990). In this study, an attitudinal survey was designed to compare PT users' perceptions and attitudes toward various events; the respondents included regular and occasional users. The questionnaire consisted of four parts: socio-economic and trip information, users' preferences and expectations as criteria for selecting PT over car, users' attitude and decision toward different waiting times, and lastly their attitudes toward and decisions about some selected real-time operational tactics.

#### 8.3.1 Design of Questionnaire

Attaining the study's objectives is done by the use of a questionnaire. All the considered factors, of this questionnaire, are in line with a solid theoretical base to support it (Nesheli and Ceder, 2014, 2015b). The questionnaire is five-fold. The first part contains general questions and a demographic survey. The second part refers to the use of smartphone application. The third part is used as a decision support tool using state-of-preference type of questions. That is, given a certain real-time information displayed on the smartphone, there are four travel scenarios (solutions) to select from under three main categories: (1) given that the bus is delayed by different times, (2) given that the use of operational tactics can make the PT better than the car in terms of travel time and comfort, and (3) given that the use of operational tactics can save travel time. The fourth part was designed to investigate user's perception of value of time perceived for the four travel scenarios when implementing an operational tactic. The fifth part is a proportional evaluation of four criteria: travel time, PT reliability, comfort, and energy; Likert score from 1 (not important) to 5 (very important) was used for this evaluation of knowing

when the PT service is preferred over the car. In addition the questionnaire was designed to evaluate the risk-perception level of the respondents concerning their decisions.

In travel behavior studies, it has been a common practice to assume that travelers have a perfect knowledge about their choices and make rational decisions based on utility maximization (Xu et al., 2011).

### **8.3.2 Data Collection and Survey Implementation**

The decision tool, based on the application adapted to a smartphone, must be adaptable to any network from any city in the world. Some of the variables and parameters could be independent of the network and the level of service; some could differ among cities. To assess these differences, the same survey was conducted in two cities with different characteristics: Auckland in New Zealand, and Lyon in France. The application had to consider and adapt to all the passengers. Thus, the survey locations were carefully chosen to capture the most varied characteristics of PT users as possible.

The Britomart Transport Center in Auckland was chosen as one survey location. Britomart is Auckland CBD's main PT hub. All vehicles entering and leaving this CBD begin and end their trip at Britomart. The hub provides a link to the main bus, train, and ferry services of the Auckland region, thus allowing PT users an opportunity to make transfers in Britomart. This location, then, offers the most diversified population of Auckland's PT users. The Laurent Bonnevey station in Lyon was chosen as the second survey location. Laurent Bonnevey is the most important hub in the west of the city. Most of the western bus lines stop at this station, which is a transfer point linking to a subway network. In addition, a park-and-ride site enables car drivers from the western suburbs or further away to park their car before using PT. The choice of this hub, too, provides a varied population of users.

The survey was conducted between 0700 and 1800 on seven weekdays to capture both commuter and non-commuter PT users. Data from 290 and 321 participants in Auckland (Case 1) and Lyon (Case 2), respectively, was collected. Although the two cases each present a diversified user population, the characteristics of Lyon's PT network and its users' trip attitudes differ considerably from those of Auckland.

### 8.3.3 Public Transport Service Factors and Application

#### *Effects of Service Factors on Users' Perception*

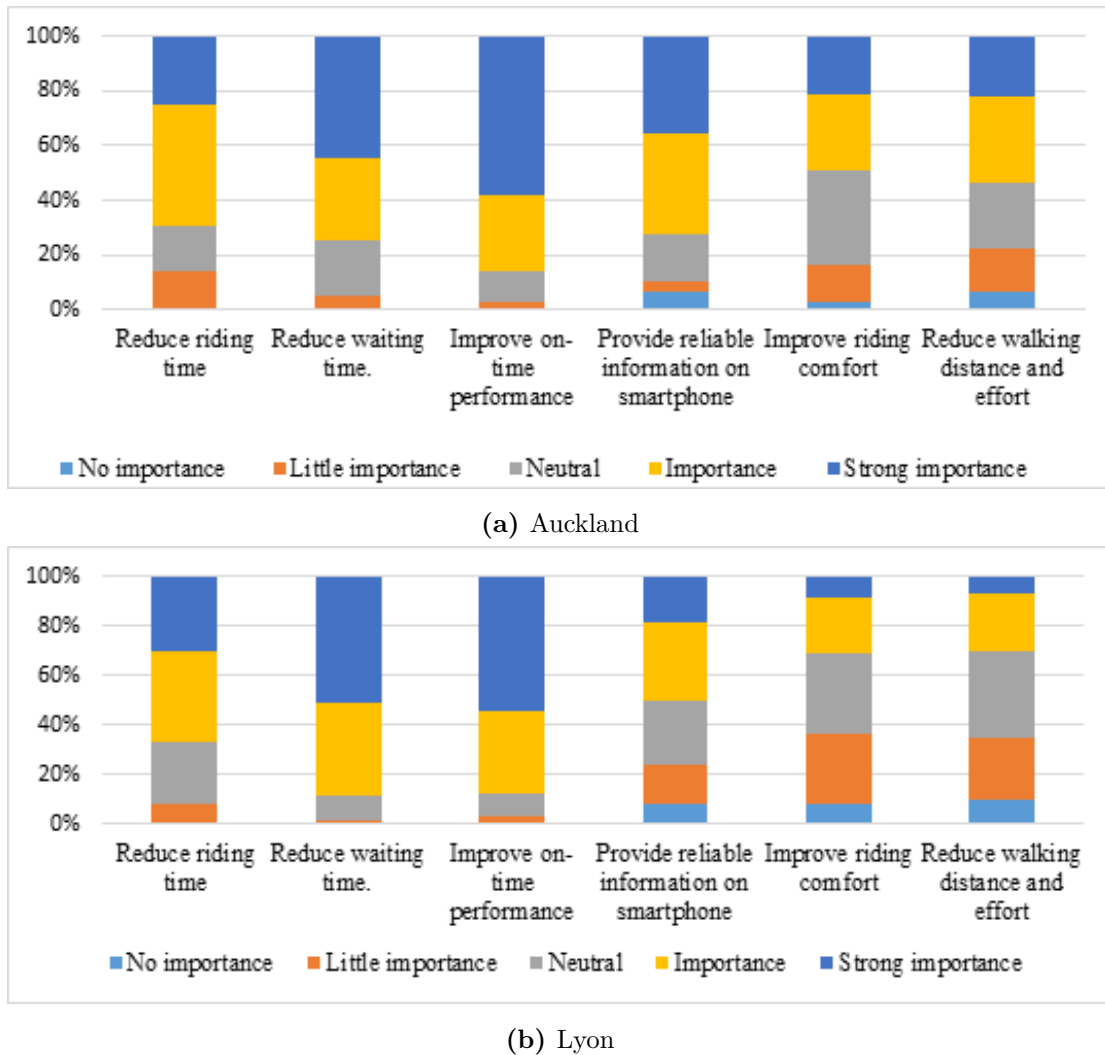
Generally speaking, owing to convenience, speed, comfort, and individual freedom, car is the most attractive mode of transportation (Anable, 2005). Thus, in order to reduce car use, it is necessary to understand the underlying criteria of users' preferences for and expectations of PT services. Respondents from the two cities sampled were asked to give a score from 0 (no importance) to 5 (strong importance) on several proposed improvements in PT service. As Figure 8.1 shows, the first thing to be noted is that the tendency is the same in both cases even if there is some change in ratio. The strongest importance (i.e., receiving a score of 5 is associated with improving on-time performance); on average, 55% of the respondents in both cities thought so. Not far below that service factor, the reduction in waiting time was strong in importance for 50% of the respondents on average in both cases. Providing reliable information on smartphones seems to be important for users, too. This study, then, demonstrates how important an improvement in the reliability of PT service is to passengers.

#### *Use of the Application*

The study as a whole and especially the following models assume that the users know in real time both the position of vehicles and the estimated vehicle arrival time at every stop. This information would be based on an application adapted to smartphones. To assess the potential use of such an application and the interest of passengers, respondents were asked whether they would be ready to use such an application as a decision-support tool. In Case 1, 91% asserted they were ready as did 82% of the respondents in Case 2. Giving passengers such a decision-support tool appears to cover an important part of their PT need and, therefore, justifies the requirement for this study.

## 8.4 Decision Models

To assess PT passengers' perceptions and expectations of the potential features of a decision-support tool, two models were used. These models describe the pattern of PT users' decisions toward different situations. In order to select an appropriate model describing users' decisions profoundly, various statistical analyses has been investigated.



**Figure 8.1:** Assessment of service factors proposed for the improvement of PT services

Considering the nature of the data sets in which both independent and dependent variables are categorical (nominal) led to employ the Multinomial Logistic Regression (MLR) analysis. The MLR method is the most suitable technique for dependent variables with more than two-level category (Hosmer Jr and Lemeshow, 2004, Janssens et al., 2008, Menard, 2002). It is to note that the reason behinds designing the questionnaire, based on categorical data, was to group the users' preferences by type of feasible solutions to select, thus enabling to make direct inferences. Table 8.1 shows a description for each decision, or for each level considered. Consequently, a decision tree (DT) method was used to classify the respondents; this classification is to examine whether or not a set of variables is effective in predicting category memberships to validate the MLR outcome. The decision-support tool is for the use of both the planners and passengers. That is,

**Table 8.1:** List of scenarios

Decisions	Descriptions
Wait at the stop	Passengers will stay at the stop during the announced delay time of the PT vehicle.
Walk to another stop	Passengers will select to walk to another stop either on the same route or other nearby routes.
Wait and do something else	Passengers will do something else during the announced delay time of the PT vehicle, e.g., shopping around the stop.
Won't use PT	Passengers will leave the stop and use another travel (or walking) mode, e.g., private car.

comprehension of the importance of how passengers prefer to manage their time.

### 8.4.1 Multinomial Logistic Regression Model

#### *Significance of Independent Variables*

Table 8.2 depicts the correlations of this study's independent variables. As all these variables are categorical, an ordinary correlation test calculating the Pearson ratio was not used. Thus, the V-Cramer coefficient was chosen as an alternative to the r-Pearson coefficient to assess the correlation between variables (Sheskin, 2003). The V-Cramer coefficient is based on the Chi-Square ( $\chi^2$ ), the classic statistical test that assesses if the distributions of a categorical variable differs from another in the whole population. It is calculated based on the data of the sample ranked in a contingency table, and compares the frequencies observed and expected (Equation 8.1). The value of the  $\chi^2$  itself cannot be used to assess the strength of the correlation between the variables.

The V-Cramer coefficient is adapted from the  $\varphi$  coefficient, which is the equivalent of the r-Pearson coefficient for qualitative variables. The V-Cramer can be calculated for variables divided into more than two groups, which is the case here. It should be noted that this coefficient is not dependent on the number of categories in the sample.

$$V = \sqrt{\frac{\chi^2}{N * \min(r - 1)(c - 1)}} \quad (8.1)$$

Where:  $N$  = population of the sample;  $c$  = number of columns of the contingency table; and  $r$  = number of rows of the contingency table. The V-Cramer coefficient lies between 0 and 1. The closer the coefficient is to one, the stronger is the correlation between variables. As in any statistical test, two hypotheses were tested. The first was the null hypothesis  $H_0$ , which stipulates that the correlation between variables is due to coincidence; in other words, there is no correlation in the population. The alternative hypothesis  $H_1$  stipulates, to the contrary, that a correlation cannot be due to coincidence and that it can be extrapolated to the population. The significance number (Sig) calculates the probability that the result found in the sample (here, the correlation) can be extrapolated to the population. In this study, the minimum risk of error will be chosen as  $\alpha = 0.05$  as is typical in human sciences. Thus, if  $\text{Sig} > 0.05$ ,  $H_0$  must be accepted, and the conclusion is that the variables are independent.

**Table 8.2:** Results of Independence Tests

Case 1

Variable	Age	Occupation	Commuter	Origin	Destination	Purpose	Travel time	Transfers
Gender	(0.319 ; 0.050)	(0.277 ; 0.314)	(0.042 ; 0.686)	(0.158 ; 0.527)	(0.143 ; 0.609)	(0.211 ; 0.261)	(0.299 ; 0.159)	(0.106 ; 0.325)
Age		(0.687 ; 0.000)	(0.265 ; 0.091)	(0.179 ; 0.476)	(0.146 ; 0.773)	(0.502 ; 0.000)	(0.267 ; 0.211)	(0.250 ; 0.145)
Occupation			(0.345 ; 0.090)	(0.256 ; 0.492)	(0.285 ; 0.248)	(0.638 ; 0.000)	(0.250 ; 0.575)	(0.366 ; 0.074)
Commuter				(0.185 ; 0.386)	(0.113 ; 0.770)	(0.463 ; 0.000)	(0.250 ; 0.352)	(0.328 ; 0.002)
Origin					(0.198 ; 0.316)	(0.167 ; 0.593)	(0.473 ; 0.001)	(0.190 ; 0.376)
Destination						(0.180 ; 0.466)	(0.270 ; 0.192)	(0.221 ; 0.241)
Purpose							(0.300 ; 0.064)	(0.441 ; 0.001)
Travel time								(0.478 ; 0.001)

Case 2

Variable	Age	Occupation	Commuter	Origin	Destination	Purpose	Travel time	Transfers
Gender	(0.085 ; 0.625)	(0.186 ; 0.105)	(0.117 ; 0.181)	(0.238 ; 0.062)	(0.136 ; 0.494)	(0.154 ; 0.543)	(0.206 ; 0.356)	(0.003 ; 0.970)
Age		(0.586 ; 0.000)	(0.237 ; 0.026)	(0.223 ; 0.045)	(0.097 ; 0.873)	(0.407 ; 0.000)	(0.194 ; 0.460)	(0.030 ; 0.941)
Occupation			(0.161 ; 0.187)	(0.289 ; 0.001)	(0.135 ; 0.565)	(0.504 ; 0.000)	(0.221 ; 0.240)	(0.067 ; 0.747)
Commuter				(0.339 ; 0.002)	(0.586 ; 0.000)	(0.594 ; 0.000)	(0.263 ; 0.110)	(0.145 ; 0.098)
Origin					(0.531 ; 0.000)	(0.289 ; 0.001)	(0.232 ; 0.138)	(0.212 ; 0.119)
Destination						(0.492 ; 0.000)	(0.499 ; 0.000)	(0.317 ; 0.005)
Purpose							(0.249 ; 0.055)	(0.159 ; 0.508)
Travel time								(0.407 ; 0.001)

Note: The values shown are the P-Values of the V-Cramer coefficient.



The tests demonstrate that there is correlation between some variables. For instance, there is a correlation among travel time, origin, and destination. This correlation is easily explained: the further away the origin of people's trips from their destination, the longer will be their travel time. Correlated information is available, but only the travel time, the most prominent in the data set, will be retained. In the same way, occupation is strongly correlated with the purpose of the trip (0.638; 0.000) in Case 1 and (0.504; 0.000) in Case 2. This variable, then, will be ignored. Finally, five variables will be maintained for this study: gender, age, purpose of trip, travel time, and transferring.

### *Model Building*

Logistic regressions are widely used in various fields to assess the likelihood of certain events. MLR is a statistical tool used to assess and predict the impact of independent variables on a dependent variable. It is the best tool when the variables are categorical and composed of more than two groups or categories (Menard, 2002). Compared with the other statistical methods, MLR has the advantage that it can be performed without strongly adhering to the normality of the data, a situation that is often not attained in practice (Kleinbaum, 1994). Equation 8.2 gives the formula for a multinomial logistic regression:

$$Pr(y_i = j) = \frac{\exp(x_i \beta_j)}{\sum_j \exp(x_i \beta_j)} \quad (8.2)$$

Where:  $Pr(y_i = j)$  is the probability of belonging to group  $j$ ;  $x_i$  is a vector of explanatory variables; and  $\beta_j$  are the coefficients, which are estimated using the maximum likelihood estimation.

In order to test the model, a typical PT service situation was chosen: the wait at a stop when the vehicle is delayed. This situation especially happens in the case of bunching. It was noted that the better the operator can forecast the passengers' behaviors, the more likely a good decision will be made, using a good tactic and thus improving the reliability of the service. Assuming that with the application, users are informed of the situation in real time. A model can be built that allows passengers to decide whether to wait at a stop for "0-5 minutes", "5-10 minutes", "10-15 minutes", or "more than 15 minutes". For each of these delay times, respondents were asked for their choice across

four decisions: "wait at the stop", "walk to another stop", "wait and do something else during the time advised", and "not to use PT or to use another mode".

For every answer, the gender, age group, purpose, and average travel time of the passenger are known, as well as if the respondent does or does not transfer during the trip. The sixth parameter taken into account is the delay time of the vehicle. The dependent variable is the decision of the passengers. The impact of these independent variables on the dependent variable is assessed using the following equation:

$$y_{decision} = f(X_{delay}, X_{age}, X_{traveltime}, X_{gender}, X_{purpose}, X_{transfers}) \quad (8.3)$$

#### *Results of the Multinomial Logistic Regression model*

Table 8.3 illustrates the results of the regression model analysis. The MLR in Case 1 is statistically significant ( $\chi^2 = 266$ , Sig < 0.001). The model explains 57% of the variance in the passenger's decision. Four predictors are significant in this model: delay ( $\chi^2 = 201.9$ , Sig = 0.000), age ( $\chi^2 = 20.54$ , Sig = 0.02), purpose ( $\chi^2 = 30.11$ , Sig = 0.000), and travel time ( $\chi^2 = 33.05$ , Sig = 0.01). Goodness-of-fit tests = 0.989 » 0.05 indicate that the model is appropriate for analyzing the data. It should be noted that  $X_{gender}$  and  $X_{transfers}$  were not significant in the first regression analysis.

In Case 2, the model is also statistically significant ( $\chi^2 = 590.129$ , Sig < 0.001). The model explains 75% of the variance in the passenger's decision. Four predictors are significant in this model: delay ( $\chi^2 = 557.8$ , Sig = 0.000), purpose ( $\chi^2 = 60.5$ , Sig = 0.042), travel time ( $\chi^2 = 27.4$ , Sig = 0.028), and transfers ( $\chi^2 = 7.9$ , Sig = 0.048). Goodness-of-fit tests = 0.990 » 0.05 indicate that the model is appropriate. It should be noted that  $X_{gender}$  and  $X_{age}$  were not significant in the first regression analysis.

#### *Discussion of Output*

Table 8.3 and Figures 8.2 and 8.3 summarize and illustrate the results of each independent variable on users' decisions. Figures 8.2 and 8.3 describe the tendency to make a decision based on each predictor category.

*Delay:* The results of both case studies show that delay is the most significant factor for the dependent variable. In both cases, more than 80% of the users will wait at the stop

**Table 8.3:** Results of Independence Tests

Case 1				
Model Analysis		Chi-Square	df	Sig.
Model Likelihood Ratio Tests		266.071	42	0.000
Goodness-of-fit of the model (Pearson)		326.325	387	0.989
Parameter Likelihood Ratio Tests	$X_{delay}$	201.90	9	0.000
	$X_{age}$	20.54	9	0.015
	$X_{purpose}$	30.11	9	0.000
	$X_{traveltime}$	33.05	15	0.015
Pseudo Nagelberke- $R^2$		0.572		

Case 2				
Model Analysis		Chi-Square	df	Sig.
Model Likelihood Ratio Tests		590.129	33	0.000
Goodness-of-fit of the model (Pearson)		139,593	252	0.990
Parameter Likelihood Ratio Tests	$X_{delay}$	577.892	9	0.000
	$X_{purpose}$	60.522	6	0.042
	$X_{traveltime}$	27.359	15	0.026
	$X_{transfers}$	7.991	3	0.046
Pseudo Nagelberke- $R^2$		0.754		

for a delay time of less than 10 minutes, and users are 23 times more likely to wait if the delay time announced is less than 5 minutes than if it is 15 minutes. When the users were informed that the delay would be greater than 10 minutes, more than 60% of them in both cases were willing to act. The options available to users are either to "walk to another stop" or "do something else". In Lyon, users' were more likely to walk to another stop because of the dense network. In Auckland, the hilly terrain and service unreliability were the main reasons for users' likely choosing the option of "do something else".

*Age:* Age was statistically significant only in Case 1. Based on the regression model, users who are younger than 25 years old are 2.7 less likely to wait at the stop and 1.8 more likely to walk to another stop than are older users (more than 60 years old). Age was not a significant factor in Case 2, as the network in Lyon is denser. The grid structure of Lyon's network requires travelers to exert less effort in changing their route.

*Purpose:* The purpose of the trip also significantly impacts the decision in both cases. The main difference found was between "professional and studies" and "leisure, shopping, and others". In the first group, users are more constrained by time and, therefore, less likely to "wait at the stop" or "wait and do something else".

*Travel Time:* Usually, the longer the users' travel time, the greater is the wait-time portion of this travel time. According to the model, for users' travel time greater than 30 minutes, the probability of waiting at the stop is three times the probability of having a travel time less than 30 minutes, and twice concerning "wait and do something else". In other words, the longer the travel time, the larger is the number of users to tolerate extra waiting, either at the stop or by doing something else. The findings are similar for Case 2.

*Transfers:* This factor was significant only in Case 2. Users who make transfers are 1.3 times more likely to "wait at the stop" or "walk to another stop" than are other users. Most of the passengers who have to transfer have a route that is previously planned, and so they do not want to miss the connecting vehicle. Thus, either they wait at the stop for the next vehicle or they attempt to reach another stop.

#### 8.4.2 The Decision Tree Model

Classification is an important learning algorithm in a data-mining problem. In order to classify the importance of each independent variable for the decision-making process, a decision-tree (DT)-based model was used. The DT, which is simple and easy to understand, can be used to identify high or low-risk homogeneous groups. In addition, this model makes it easy to construct rules for making predictions about individual cases (Kass, 1980). There are several DT-based methods, including Chi-squared Automatic Interaction Detection (CHAID). Unlike other DT-based algorithms, it CHAID allows multiple splits of a node. At each step, CHAID chooses the independent variable that has the strongest interaction with the dependent variable. Categories of each predictor are merged if they are not significantly different with respect to the dependent variable. For each node, the p-value (significance), the Chi-square, and the degree of freedom correspond to the Likelihood Chi-square test. The risk estimate is an indicator of model performance.

##### *The Results*

As Figure 8.4(a) shows, the risk estimated (0.383) is quite low, which indicates a fairly good model, which predicts about 62% of the decisions correctly. In this model, as for the MLR model, delay is the most significant independent variable and corresponds to the first node. Purpose, which is the second most significant predictor, determines the separation of decisions. The two groups "Professional" and "Studies" were merged

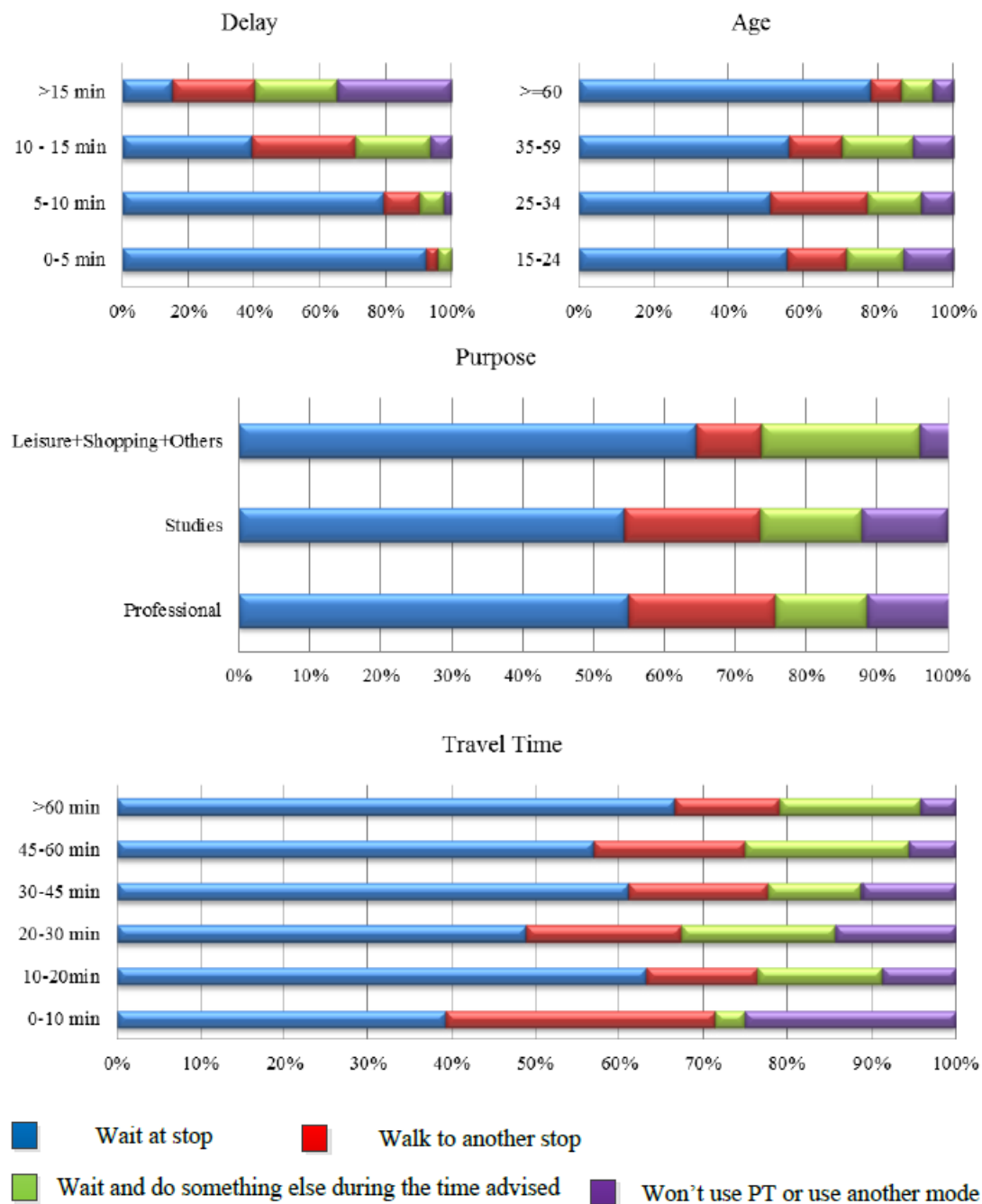


Figure 8.2: Impact of independent variables on passengers' decisions, Case1.

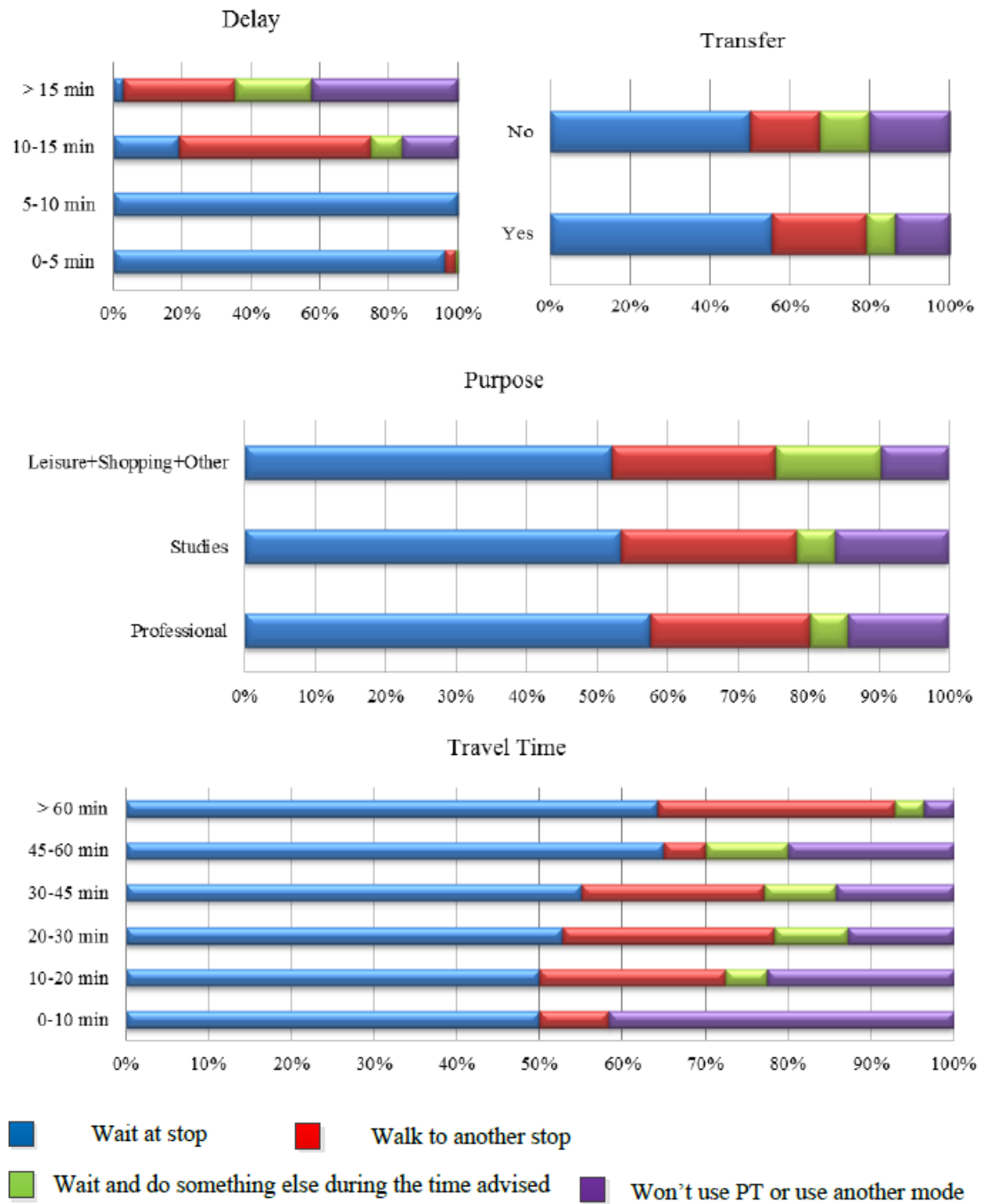


Figure 8.3: Impact of independent variables on passengers' decisions, **Case2**.

because they were not sufficiently significant separately. CHAID associates the first branch, composed of "Professional and Studies", with the decision of "walking to another stop". The second group, composed of "Leisure", "Shopping", and "Others", is associated with the decision of "waiting at the stop".

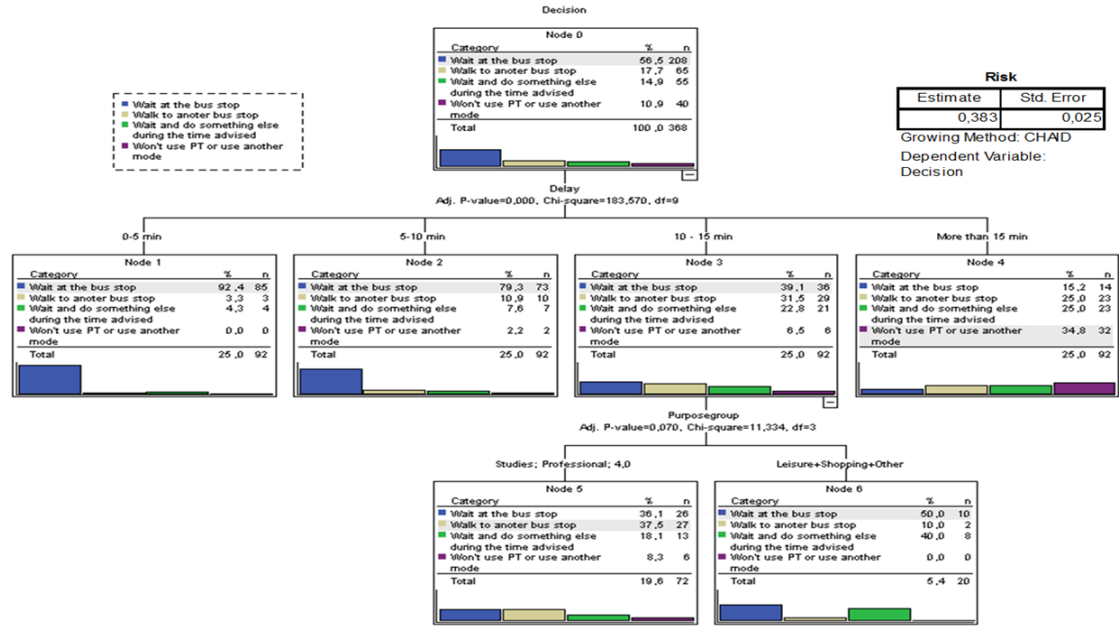
In Case 2, Figure 8.4(b) shows that the risk estimated (0.265) is low, which indicates a good model. The quality is even better than Case 1, since the model predicts an overall percentage of 73.5% of the decisions correctly. The results of the analysis are close to Case 1 with the delay variable as the first predictor variable, dividing the root node significantly. In the last delay group, corresponding to a delay of more than 15 minutes, the transfer independent variable is chosen to separate the decisions. It should be noted that the conclusions of the DT model correspond to those found with the MLR model.

## **8.5 STAGE 2: Effects of Tactics on Users' Perception and Decision**

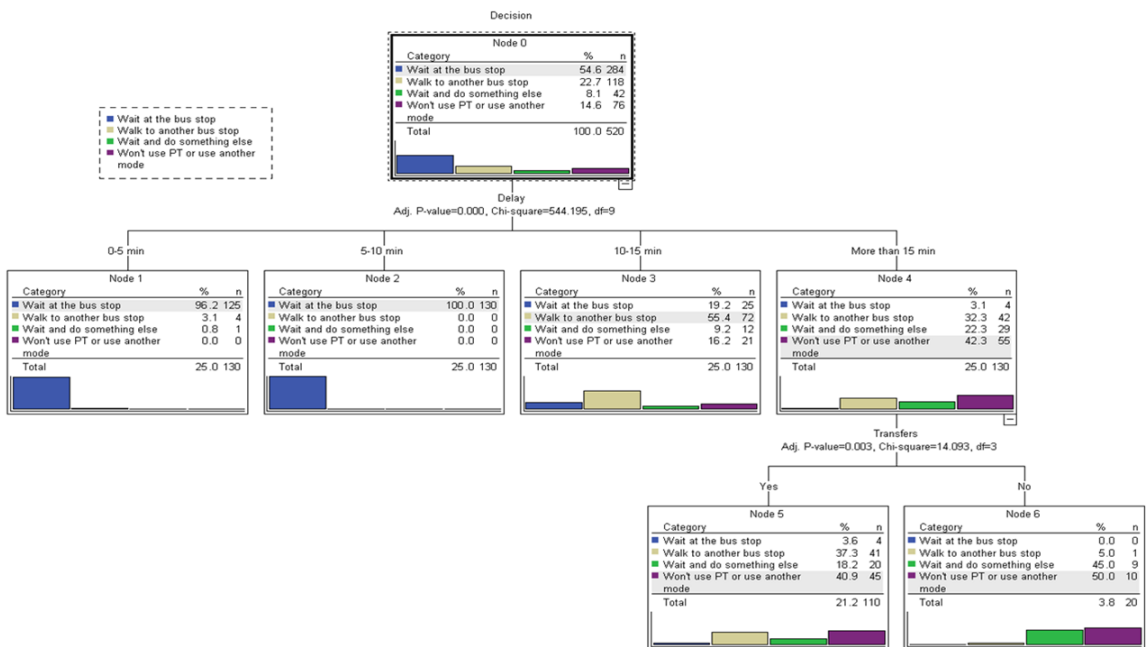
The findings of the previous section suggest that policy-makers and PT operators are required to focus on the methods of reducing the uncertainty in real-time operations. In other words, they should provide real-time information and implement proper operational control actions based on users' decisions so as to increase the attractiveness of PT by enabling a more efficient, integrated network. In this section, the effect of using different real-time control actions to improve PT service and making it better than the car mode in terms of travel time and comfort is investigated. A questionnaire was designed to measure PT users' perception of certain operational tactics whose purpose is to improve the PT service, especially when an unexpected event leads to a deterioration of service.

### **8.5.1 Operational Tactics**

The tactics chosen to be tested were "holding", "skipping", and "boarding limits"; the third tactic is treated as skipping passengers and was merged with the second. For "holding", two situations were considered: if users are onboard at a holding point, and whether they are seated or standing on the vehicle. For "skipping", two situations were also presented: potential passengers waiting at a stop are informed that the vehicle will not stop; the



(a) Case1



(b) Case2

Figure 8.4: Decision-tree output of passengers' decisions



vehicle is considerably late and waiting passengers are advised to walk to another stop or go directly to their destination by another transport mode. To make these tactics as efficient as possible, it is important to measure the degree to which PT users can tolerate them. If the level of tolerance is exceeded, the main risk is that passengers will change their plans and no longer use PT services. To measure this tolerance, passengers were asked how many extra minutes they were prepared to bear waiting in several scenarios. This question refers to two scenarios: tactic without a bonus and tactic with a bonus.

### 8.5.2 Tolerated Time Model

To assess the likelihood of a tactic in a user's perception, the decision categories developed in stage one were used as variables for the running of MLR analyses. MLR produces a logistic equation that enables computation of the probability of occurrence of the dependent variable as a function of the independent variables. The MLR model predicts the odds of an event occurring. If  $P$  is the probability of an event, then the odds of that event occurring are

$$\text{odds} = \frac{P}{(1 - P)} \quad (8.4)$$

The probability function can be presented as:

$$\ln\left(\frac{P}{1 - P}\right) = \beta_0 + \beta_1 I_1 + \cdots + \beta_n I_n \quad (8.5)$$

In general, Equation 8.5 can be expressed as follows:

$$P = \frac{1}{1 + e^{-(T)}} \quad (8.6)$$

Where  $T = \beta_0 + \beta_1 I_1 + \cdots + \beta_n I_n$ ;  $T$ = tactics;  $\beta_0$ = constant;  $\beta_n$ = coefficient estimated from the data; and  $I_n$ = independent variables.

Multicollinearity in the MLR model is detected by examining the standard errors for the coefficients. A standard error larger than 2.0 indicates numerical problems, such as multicollinearity across the independent variables, and zero cells for a dummy-coded independent variable because all of the subjects have the same value for the variable

(Hosmer Jr and Lemeshow, 2004). It should be noted that we are not interested in the standard errors associated with the intercept.

For this study, "holding-seated" and "skip stop-wait" were considered for both Case 1 and Case 2. Table 8.4 details the independent variables and illustrates a divided group. Note that the reference category of dependent variables is the last category, in which users bear the maximum extra time to make the operational tactic happen; i.e., "more than 15 min".

**Table 8.4:** Independent Variables of the MLR Model

Group\ Variables	$G_1$	$G_2$	$G_3$	$G_4$	$G_5$	$G_6$
Age (year)	15-24	25-34	35-59	More than 60*	-	-
Travel time (min)	0-10	10-20	20-30	30-45	45-60	More than 60*
Purpose	Professional	Studies	Leisure+ Shopping+ Other*	-	-	-
Delay	Wait at the stop	Walk to another stop	Wait and do something else during the time advised	Won't use PT or use another mode*	-	-

\*For each variable, the last group is the reference group.

#### *Holding:*

The final model in Case 1 is statistically significant and predicted the dependent variable over and above the intercept-only model ( $\chi^2(88) = 234.564, P < 0.001$ ). The model explains 53% (Nagelkerke  $R^2$ ) of the variance in a passenger's decision in a holding tactic. Similarly, the model in Case 2 is statically significant ( $\chi^2(72) = 211.753, P < 0.003$ ), explaining 55% (Nagelkerke  $R^2$ ) of the variance in a passenger's decision in a holding tactic. Table 8.5 summarizes the model's results, which show the estimated coefficients and the related statistics of the MLR models developed. The table also shows the combination of a constant and the statistically significant variables identified in each MLR model developed for each of the tactics. For example, the results in Case 1 for the holding tactic of "0-2.5 min" can be represented as follows:

- Compared with "more than 60-year old" users, users from 35-59 years old are 37.75 times more likely to tolerate "0-2.5 minutes" extra time than "more than 15 minutes"

of a holding tactic.

- In comparison with more than 60 minutes of travel time, passengers who have to travel only 20-30 minutes are 75.94 times more likely to tolerate "0-2.5 minutes" of extra time than "more than 15 minutes" of a holding tactic.
- In comparison with "won't use PT or [will] use another mode" when there is a 15-minute delay, people who decide to "wait at the stop" are 6.48 times more likely to tolerate "0-2.5 minutes" of extra time than "more than 15 minutes" of a holding tactic.
- In comparison with "won't use PT or use another mode" in a 15-minute delay, those who decide to "walk to another stop" are 2.86 times more likely to tolerate "0-2.5 minutes" extra time than "more than 15 minutes" of a holding tactic.
- In comparison with "no transfer", passengers with a transfer are 4.62 times more likely to tolerate "0-2.5 minutes" extra time than "more than 15 minutes" of a holding tactic.

Consequently, the prediction model of a holding tactic of "0-2.5 min" is estimated with the following equation:

$$T_{Holding(0-2.5)} = -11.84 + 3.63I_{Age(35-59)} + 4.33I_{Traveltime(20-30)} + 2.62I_{Traveltime(30-45)} + 1.87I_{Delay(Wait\ at\ the\ stop)} + 1.05I_{Delay(Walk\ to\ another\ stop)} + 1.53I_{Transfer(Yes)} \quad (8.7)$$

To illustrate the use of the MLR model developed, consider the probability of event (1) versus non-event (0) for each independent variable. Substituting event-input data into the prediction model with a "Holding (0-2.5)" option, as in Equation 8.7, is found to yield 3.19 (see Equation 8.8).

$$T_{Holding(0-2.5)} = -11.84 + 3.63(1)_{Age(35-59)} + 4.33(1)_{Traveltime(20-30)} + 2.62(1)_{Traveltime(30-45)} + 1.87(1)_{Delay(Wait\ at\ the\ stop)} + 1.05(1)_{Delay(Walk\ to\ another\ stop)} + 1.53(1)_{Transfer(Yes)} \quad (8.8)$$

Therefore, the probability of the occurrence of "Holding (0-2.5)" can be obtained by substituting it in Equation 8.6, producing Equation 8.9.

$$P = \frac{1}{1 + e^{-(T_{Holding}(0-2.5)})} = \frac{1}{1 + e^{-(3.190)}} = 0.960 \quad (8.9)$$

The result suggests that the input variables have a 96% probability of attaining a holding tactic outcome of 0-2.5 minutes. Thus, implementing holding time in this range would be effective considering the attributes above mentioned.

#### *Skip-Stops:*

The skip-stops model in Case 1 is statistically significant, ( $\chi^2(88) = 248.743, P < 0.001$ ) and explains 51% (Nagelkerke  $R^2$ ) of the variance in a passenger's decision during this tactic. The model in Case 2 is also statistically significant ( $\chi^2(72) = 232.552, P < 0.002$ ), explaining 53% (Nagelkerke  $R^2$ ) of the variance in a passenger's decision during a holding tactic. Table 8.6 depicts the estimated coefficients and related statistics of the MLR models developed for the skip-stops tactic in both cases.

From the information in Tables 8.5 and 8.6, it can be concluded that if the likelihood of being in the category of a tactic for each of the independent variables versus a reference category is not statistically significant, the user appears to have the same opinion when it comes to the current tactic category. The analysis also indicates that none of the independent variables had a standard error larger than 2.0. Moreover, the analysis shows that the skip-stop tactic is sensitive to delay, with users experiencing longer delay being less likely to "wait at the stop" or "wait and do something else". Thus, operators should pay attention to this fact when they consider using such a tactic.

Table 8.5: MLR Model of Tolerated Holding Time

Case 1

Dependent variable	Variable	G	B	SE	Wald	df	Sig	Exp(B)	95% CI for Odds Ratio	
									Lower	Upper
Holding	Age	3	3.63	1.52	5.69	1	0.017	37.757	1.910	746.223
	Travel time	3	4.33	0.95	341.18	1	0.001	75.944	6.800	252.502
	Delay15 min	4	2.62	1.01	297.27	1	0.001	13.735	1.021	119.752
	Transfer	1	1.87	0.95	267.24	1	0.000	6.488	1.357	31.263
	Constant	2	1.05	0.92	340.04	1	0.000	2.857	1.122	13.714
		1	1.53	0.69	4.89	1	0.027	4.678	1.087	16.322
		-11.84	3.34	28.35	1	0.198				
	Age	3	2.71	1.30	4.34	1	0.037	15.079	1.174	193.721
	Travel time	5	-3.73	1.37	7.39	1	0.007	0.024	0.002	0.352
	Delay10 min	1	-6.34	1.68	93.95	1	0.004	1.76E-03	2.95E-05	2.18E-01
5-10 min	Constant	3	-5.68	1.49	140.79	1	0.000	3.41E-03	1.14E-05	3.90E-01
		15.76	2.73	57.65	1	0.002				
	Age	1	-5.07	1.22	17.21	1	0.005	0.006	0.001	0.069
	Travel time	2	-3.66	1.21	9.19	1	0.002	0.026	0.002	0.274
		5	-3.06	1.46	4.38	1	0.036	0.047	0.003	0.822
	Purpose	2	3.00	0.88	11.57	1	0.001	20.079	3.566	113.067

	Delay10 min	1	-3.02	1.11	184.76	1	0.003	0.048	0.0001	0.098
		2	-4.26	1.23	154.07	1	0.004	0.014	0.0003	0.087
	Constant	17.95	2.76	42.24	1	0.001				

G: group; B: B-coefficient; SE: standard error; Wald: Wald chi-square test; df: degrees of freedom.

Case 2

Dependent variable	Variable	G	B	SE	Wald	df	Sig	Exp(B)	95% CI for Odds Ratio	
									Lower	Upper
0-2.5 min	Age	2	3.63	1.52	15.69	1	0.020	37.757	1.910	746.22
		3	0.46	1.50	46.09	1	0.020	1.590	1.084	30.117
	Travel time	4	-2.05	1.71	34.85	1	0.011	0.128	0.033	0.876
		1	-5.23	1.59	24.06	1	0.041	0.005	3.33E-05	0.864
	Delay more than 15 min	2	1.66	1.64	244.86	1	0.000	5.259	1.581	58.451
		1	2.63	0.89	7.89	1	0.031	13.873	1.191	23.918
	Constant		1.45	2.92	16.02	1	0.181			
	Travel time	5	-1.33	1.00	293.16	1	0.000	0.264	0.129	0.512
		2	0.95	1.13	25.70	1	0.000	2.58	1.281	23.704
	Delay15 min	3	1.29	1.74	33.55	1	0.011	3.644	2.122	110.467
Holding	Constant		2.18	3.67	27.85	1	0.081			
	Travel time	4	2.12	1.63	85.47	1	0.000	8.356	1.125	75.566
		1	0.83	1.65	63.25	1	0.021	2.295	1.091	58.683



Table 8.6: MLR Model of Time Tolerated for the Skip-Stops Tactic

Dependent variable		Case 1									
		Variable	G	B	SE	Wald	df	Sig	Exp(B)	95% CI for Odds Ratio	
0-2.5 min	Skip-Stop	Age	2	2.81	0.96	10.25	1	0.002	16.626	Lower	Upper
										1.068	21.519
		Travel time	3	3.60	1.10	10.68	1	0.001	36.811	4.235	319.958
		Delay5 min	1	2.02	1.52	3.95	1	0.047	7.538	1.287	33.959
		Delay15 min	3	-2.92	1.39	4.38	1	0.036	0.054	0.004	0.829
		Transfer	1	0.66	1.71	4.23	1	0.004	1.944	1.572	15.443
2.5-5 min	Skip-Stop	Constant		-4.34	3.46	39.56	1	0.004			
		Age	2	3.99	1.11	12.80	1	0.000	53.834	6.065	477.831
			3	2.75	1.04	13.06	1	0.000	17.796	5.577	327.13
		Travel time	4	3.86	1.09	12.58	1	0.000	47.753	5.638	404.469
			5	3.57	1.14	9.87	1	0.002	35.614	3.833	330.882
5-10 min	Skip-Stop	Delay15 min	2	0.88	1.14	6.39	1	0.011	2.40849	1.909	16.786
			3	-1.21	0.59	4.19	1	0.041	0.297	0.093	0.749
		Transfer	1	1.36	0.53	6.69	1	0.010	3.894	1.392	10.907
		Constant		-13.11	3.75	35.22	1	0.158			
		Age	2	1.83	0.80	5.23	1	0.022	6.241	1.312	29.962



	Travel time	2	4.07	0.64	1032.64	1	0.000	58.439	11.343	251.74
		3	1.09	0.54	1502.97	1	0.000	2.974	1.280	16.972
		4	0.21	0.59	1220.71	1	0.000	1.23	1.058	9.128
	Delay5 min	1	0.26	1.03	4.79	1	0.029	1.29	1.011	17.947
		2	0.81	1.04	4.05	1	0.041	2.256	1.802	26.882
	Constant	-5.85	3.66	45.45		1	0.002			

G: group; B: B-coefficient; SE: standard error; Wald: Wald chi-square test; df: degrees of freedom.

Case 2

Dependent variable	Variable	G	B	SE	Wald	df	Sig	Exp(B)	95% CI for Odds Ratio	
									Lower	Upper
0-2.5 min	Age	4	-3.59	1.37	33.25	1	0.00	0.027	0.001	0.234
	Delay5 min	1	4.41	1.27	12.13	1	0.00	82.482	6.887	987.803
	Transfer	1	2.33	1.91	11.75	1	0.031	10.277	5.572	111.443
	Constant		0.92	3.24	7.45	1	0.280			
2.5-5 min	Travel time	4	-3.32	1.61	22.31	1	1.00	0.036	0.001	0.794
	Delay 5 min	1	5.31	1.41	26.79	1	0.00	203.16	94.118	2392.71
	Constant		1.14	2.75	21.35	1	0.130			
	Travel time	3	0.44	1.57	159.07	1	0.041	1.546	1.071	33.491
5-10 min	Travel time	4	-0.59	1.13	123.07	1	0.031	0.555	0.009	0.882
	Delay 5 min	1	0.25	0.00	0.00	1	0.00	1.281	1.281	1.281

Skip-Stop

		1	-2.39	1.00	5.69	1	0.022	0.092	0.013	0.653
	Delay 15 min									
	Constant	4.47	2.66	36.53	1	0.092				

G: group; B: B-coefficient; SE: standard error; Wald: Wald chi-square test; df: degrees of freedom.

### 8.5.3 Results and Discussion

#### *Tactic Without Bonus*

Figure 8.5 illustrates that the extra time tolerated is mainly between 2.5 and 10 minutes. By comparing the extra times supported for every tactic, it may be observed that both the average and median extra times are between 5 and 10 minutes for Case 1 and between 2.5 and 5 minutes for Case 2. PT service reliability is better in Case 2 than Case 1; the denser network and the presence of other modes in Lyon (an underground, a tramway) can explain this difference. This comparison enables PT agencies and policy-makers to assess the efficiency of each tactic in regard to delay time. Table 8.7 shows the extra time supported while waiting, seated, or standing onboard at a holding point and waiting for the next vehicle at the stop, or walking to another stop in a skip-stop tactic. Onboard seated passengers at a holding situation are less tolerated than in the other cases.

#### *Tactic With Bonus Strategy*

The use of tactics has an adverse effect on some passengers. Because of the fact that the aim is to make the PT service more attractive, policy-makers can suggest promotion factors or any system of bonuses that would encourage passengers to accept these tactics. Thus, respondents in our sample were asked to list, as before, the extra time they would support in each situation, assuming that the PT company compensated with a reduced fare (50%) or equivalent bonus when employing operational tactics.

Results, shown in Figure 8.6, confirm the assumption that a system of bonuses could constitute a lever of action for operators and the PT companies by encouraging users to give more of their extra time and commit themselves through operational tactics to improve the service. More than half of the users tolerated an extra time greater than 10 minutes in Case 1 and greater than 5 minutes in Case 2 for both skipping situations (waiting at the stop and walking) and for holding (seated in the vehicle).

Table 8.7 shows that the most significant improvement is in the holding seated situation. Users tolerate a bonus on average of four more minutes in Case 1 and three more minutes in Case 2, representing an increase of, respectively, 60% and 75% of the average extra time tolerated. That the increase in the standing case is smaller can be explained, as did the respondents, by the fact that some of the users find it impossible to stand a long time in the vehicle (owing to age, disability, heavy fatigue, etc.), and therefore the bonus does

not really change this situation. The implementation of a bonus for the walking tactic represents an increase of only 2 minutes of the extra time tolerated in both cases.

**Table 8.7:** Results of Average Extra Time Tolerated

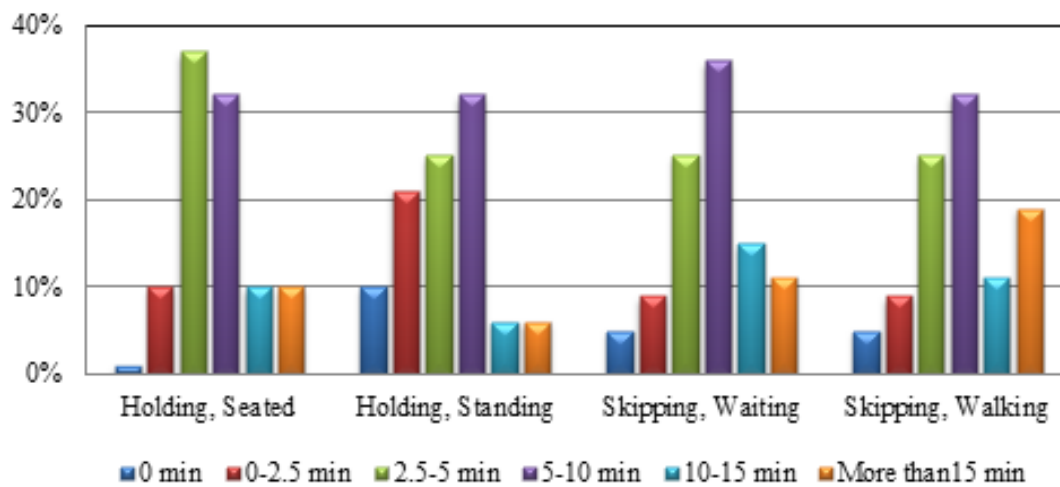
Tactics	Case1			Case2		
	Average Extra Time Tolerated (min)	Average Extra Time Tolerated + Bonus (min)	$\Delta$ Average Extra Time (min)	Average Extra Time Tolerated (min)	Average Extra Time Tolerated + Bonus (min)	$\Delta$ Average Extra Time (min)
Holding Seated	7	11	4	4	7	3
Holding Standing	6	9	3	2	5	3
Skipping Waiting	8	11	3	4	6	2
Skipping Walking	9	11	2	5	7	2

Note:  $\Delta$  means an increase in average extra time after a bonus strategy.

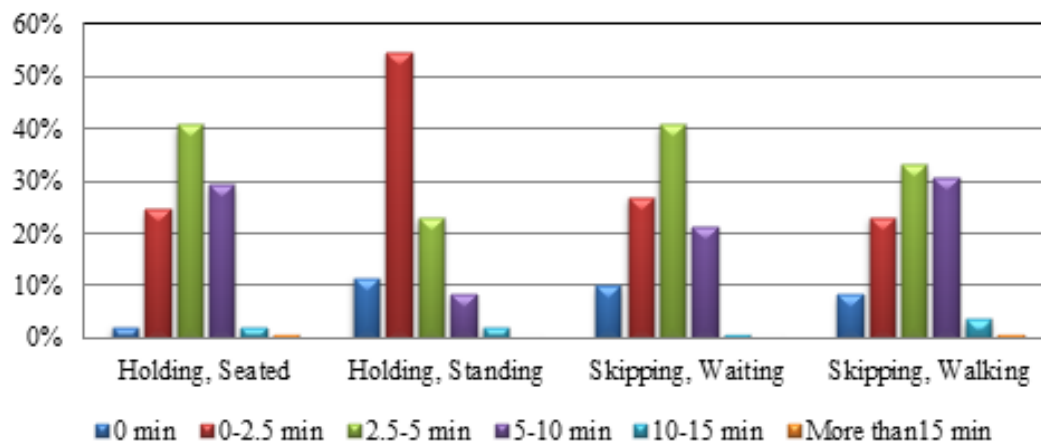
## 8.6 Conclusions and Future Research

To provide travelers with a reliable alternative to private cars and encourage a modal shift, PT agencies have adopted several tactics for developing an integrated, effective multi-modal transport system. These tactics have been widely developed and discussed in literature. Up to now, however, there has been no specific investigation of the effect of implementing tactics on passengers' perceptions and decisions (the demand side). The control of PT demand in real time represents a major advantage for both policy-makers and PT users. To support this control, a decision-support tool, such as an application adapted to a smartphone, could provide travelers with continuous online information about the PT service. The contribution of the present study is to offer PT agencies a guideline on demand control. This is undertaken in two-parts: (a) an assessment of the effects of delay on PT users' perceptions and decisions to change route or mode; (b) an evaluation of users' decisions based on various real-time operational tactics.

To attain this goal and to build the guideline, a user-decision and preference survey was conducted to investigate users' attitudes toward various control actions. To assess



(a) Case1

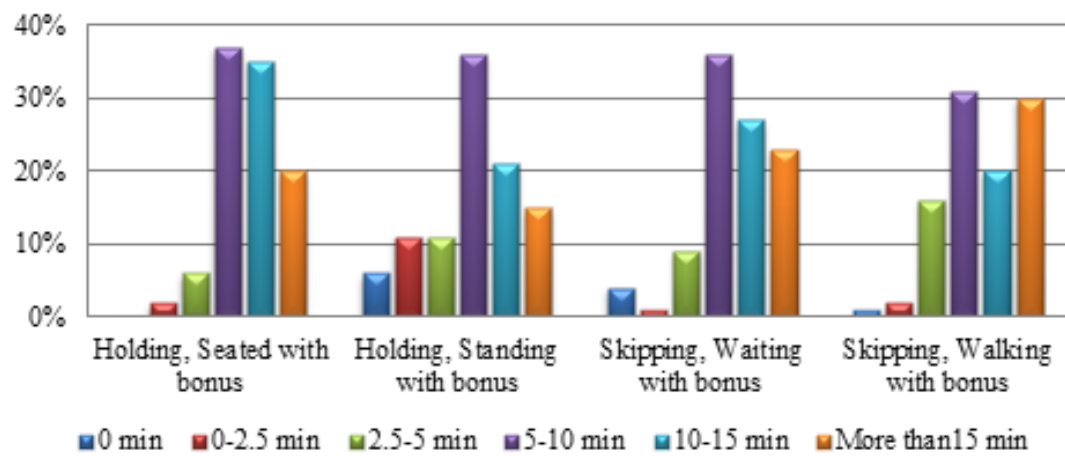


(b) Case2

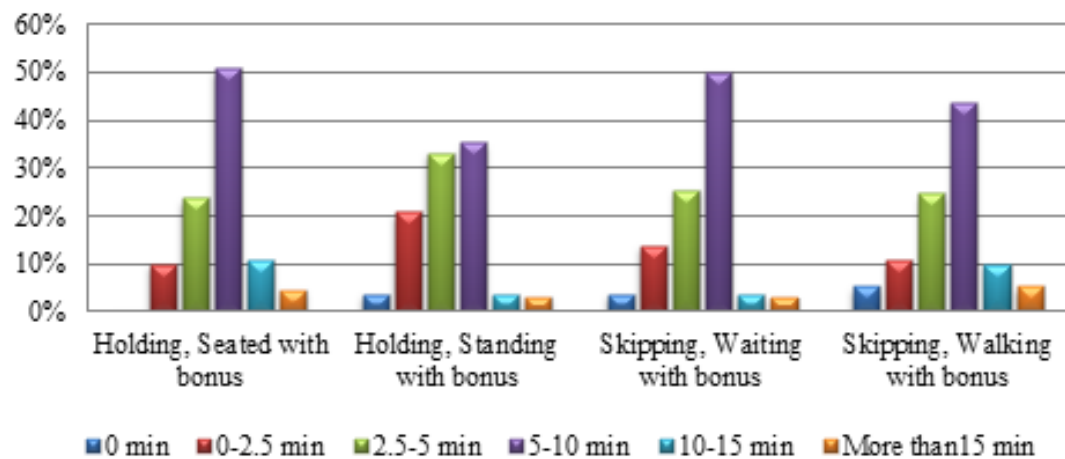
**Figure 8.5:** Extra Time tolerated by Users without a Bonus

the differences, the same survey was conducted in two cities with different characteristics: Auckland in New Zealand and Lyon in France. A statistical analysis was carried out, and decisions models were built using both Multinomial Logistic Regression and a decision-tree- based method.

A large majority of travelers in both Auckland and Lyon gave strong importance to a reduction in waiting time and improvement in real-time performance, for which they would be ready to use a decision-support tool. The statistical analysis emphasized that, in certain situations (e.g., waiting at a stop more than 10 minutes), more than 60% of the travelers would change their decision and adapt their travel behavior on the basis of such a decision-support tool.



(a) Case1



(b) Case2

**Figure 8.6:** Extra Time tolerated by Users with a Bonus

The results of the MLR model, based on an acceptable PT-user database, show that it is possible to predict the decisions of travelers. The decision-tree-based model, which used the CHAID method, confirms the predictions and provides a guideline for the situation of waiting at a stop. Both models demonstrate that the most significant predictor impacting on a traveler's decision is delay time. Some other factors, such as the purpose of trip, transfers, travel time, an even age of users, also have an impact on passenger's decision.

To complete the guideline, tolerated time models using real-time tactics were developed. Finally, statistical analysis was undertaken to assess users' perceptions of some operational tactics used by PT agencies. For certain events, the time tolerated would find the study informative in suggesting tactics according to the outcome desired. The extra times

tolerated for all the tactics depend on the characteristics of the PT service, which differ between Auckland and Lyon; on the average, it is between three and nine minutes at both cities. The average extra time is significantly increased by using a bonus strategy of up to 75% for "holding seated". An important result for policy-makers and PT agencies is the higher average extra time tolerated related to walking. The results show that although the waiting-time tolerated can be compensated by giving a bonus to users, it is difficult to do so with the extra walking time. The outcomes presented in this work will undoubtedly assist policy-makers in creating attractive PT services. Thus, operators are advised to consider the use of different tactics.

The limitation of this study is that the results presented cannot demonstrate strong conclusions, but depict a tendency. A more comprehensive and accurate study could show the tactic, the case, and the kind of passenger with which it could be efficient to propose a bonus to improve the PT service. In addition, the findings of this research can be integrated with other studies of risk perception and psychometric modelling to examine what it is the process existed, in an average sense, behind passengers' decisions.

Future research may continue to improve modeling of the PT demand and its sensitivity to different tactics. Finally, a more strategic and economic-based study could assess the extent to which a bonus strategy would be interesting for PT agencies and their users.

In continuation of [Chapter 8](#), the next chapter proposes a new study to identify an understanding of what constitutes PT service quality (SQ) at the operational level, using real time operational tactics based on user-centric performance measures.

## Chapter 9

# Public Transport Service-Quality Elements Based on Real-Time Operational Tactics

*Accepted in:*

*Transportation.*

(Nesheli et al., 2015a)

### 9.1 Abstract

Public transport (PT) real-time control actions, such as daily implementation of operational tactics, play a vital role in service reliability because of allowing for improvement of the quality of service perceived by passengers. Applying appropriate tactics leads to increased service reliability, reduced passenger waiting time, prevention of missed transfers and curtail passenger frustrations. To date, various studies have investigated the efficiency of using real time tactics and its effects on PT system performance. Yet, passenger perception related to various operational tactics remains one of the most poorly understood aspects of PT operations. The purpose of this study is to cultivate an understanding of what constitutes PT service quality (SQ) at the operational level, using real time operational tactics based on user-centric performance measures. SQ as a measure of serviceability in a PT system has been evaluated in relation to four definitive



factors: performance, information, operational tactics, and travel time. A conjoint analysis combined with cluster analysis is developed to capture the most important factors in evaluating the SQ process. Two case studies, each from a different country, have been selected. One is at a major terminal in Auckland, New Zealand, and the other in Lyon, France. The findings show which attributes are important in assessing SQ and how they vary in importance in different case studies.

## 9.2 Introduction

The capacity in contemporary society to endorse sustainable modes of transport to reduce problems resulting from the use of the private car, such as energy consumption, pollution, and traffic congestion (Dell'Olio et al., 2010) suggests great potential power. Notwithstanding, the use of public transport (PT) can contribute to more economical and efficient transportation, in terms of use of resources and travel times (Ceder, 2007, 2015). A common strategy practiced internationally by PT agencies is development of an integrated, multimodal transport system in order to provide passengers with a reliable substitute for private cars.

Arguably, one of the most challenging problems of transportation planning is shifting a significant number of car users to PT in a sustainable manner (Beirão and Cabral, 2007). Ceder (2007, 2015) suggested that an important consideration in the effort to retain existing users and attract new passengers is to improve serviceability by offering routes with seamless transfers. Notably, one of the common strategies for increasing the efficiency of a PT system and making it reliable is utilizing real time control actions (tactics). Various studies have been advanced to model PT real time control (e.g., (Delgado et al., 2012, Eberlein et al., 1999, Hadas and Ceder, 2010a, Hickman, 2001, Nesheli and Ceder, 2014, 2015b)). However, to date, it has been very difficult to evaluate the positive and negative effects of control strategies with respect to operations and passenger perceptions under real world conditions. Given the relatively new development of theory in this area, no measures currently exist for characterizing customer perceptions towards implemented control actions. The modal shift from private to PT can be achieved by understanding the criteria underlying users' preferences for PT services according to the emergence of new factors and attributes.

## 9.3 Literature Review

PT researchers and policymakers attempt to describe details about the main factors and attributes affecting service quality (SQ) for PT service delivery, in order to provide travelers with a viable alternative to private cars and increase user satisfaction (de Oña and de Oña, 2014). Subjectively, the evaluation of SQ is based on customer satisfaction surveys and the heterogeneity of passenger perceptions (de Oña and de Oña, 2014). Although some studies have shown that SQ perception is the outcome of a comparison of users' expectations with actual service performance perception (Grönroos, 1988, Parasuraman et al., 1988), others have investigated either passengers' perceptions or the perception of PT agencies and government managers (Eboli and Mazzulla, 2011, Nathanail, 2008).

Friman (2004) investigated the effect of SQ improvement in PT systems on user satisfaction based on perceived negative critical incidents in Swedish transit services. The results indicate that the passenger's satisfaction, when using PT services, is influenced by quality improvements only when they are evident to a superior degree. Consequently, Beirão and Cabral (2007) investigated a deeper understanding of users' attitudes toward PT and private cars. Their qualitative study proposed some key attributes bearing an influence on modal choice. They argued that if the level of service required by customers indeed accommodates their needs, then the potential for increasing the use of PT and attract new users may be viable.

Eboli and Mazzulla (2011) proposed a methodology to evaluate SQ based on both users' perceptions and transit agency measures. They considered an indicator which presumes an intermediate value between subjective (i.e., users' perception of, SQ) and objective (i.e., different sources of PT service data) measures of the SQ. Redman et al. (2013) investigated quality attributes of PT service that attract the private car user by using a qualitative systematic review. They showed that while the attributes of reliability and mobility are important, there are other attributes related to individual perceptions and motivations, effective in attracting car users.

In terms of adapting advanced statistical analysis to measure SQ, Eboli and Mazzulla (2007) formulated a structural equation model to explore the impact of the relationship between global customer satisfaction and SQ attributes. Iseki and Taylor (2010) developed an ordinal logistic regression model to examine customers' perceptions of

SQ and infrastructure at bus stops and a train station in metropolitan Los Angeles. Subsequently, Habib et al. (2011) proposed a multinomial logit model combined with latent variable models to investigate users' perceptions and attitudes towards transit SQ and attributes in Calgary, Canada. Their findings indicate that the people of Calgary value "reliability and convenience" over "ride comfort".

While extensive research has been conducted to investigate the SQ of PT, and to develop various operational control methods to analyze PT movement at control points, there has been no analytical study dealing with passengers' SQ perceptions and their decisions in relation to real time control actions directed at SQ. Thus, the effect of applying real time tactics as a key factor influencing SQ needs to be assessed. In an earlier attempt, Nesheli et al. (2015b) developed a method for considering the effect of applying real time tactics in a proper study of demand-side perceptions and decisions as complementary to the agent side. The study provides multinomial logistic regression and a decision tree-based method for passengers' decisions. They further showed that the extra times tolerated for all tactics depend on the characteristics of the PT service, which vary between case studies.

In this study, we develop a judgment model to analyze user perception of the SQ which may change depending on the category of passengers under consideration. The judgement model provides utility value for each factor/attribute level of SQ, and consequently for evaluation of any potential PT service scenario. To the best of the authors' knowledge, the present study provides an evaluation of the effect of real time control actions (tactic) on the SQ for the first time in the literature. It is assumed that a maximally synchronized timetable, improved customer service, and an efficient route network as the total SQ of PT service are considered at the planning phase. Therefore, the present work proposes a methodology, based on passengers' perception and decision making related to the various situations and scenarios, to find the best SQ of PT system at the operational phase. The presumed contribution of the present study is to provide PT agencies with a perception of what the effect of utilizing advanced technologies (e.g., real-time information, automatic vehicle location) and control methods on customer perception and the SQ would be.

The paper is divided into the following sections: the attribute of service quality in an advanced PT system; methodology including data collection and analysis; outcomes, including development of a conjoint model and clustering the results; and finally, conclusions, and recommendations for future study are presented.

## 9.4 Attributes of Service Quality in advanced PT system

Growing attention by practitioners, policymakers, and researchers, who have focused on the passengers' perspective has been drawn to the SQ of PT operations. A comprehensive study in New Zealand demonstrated that many attributes, normally grouped into smaller dimensions, as a frame of reference (taking 166 attributes into consideration), can be used to evaluate SQ (Murray et al., 2010). Despite the absence of a consensus regarding the nature of the SQ, there is a general understanding that it is a multidimensional construct (Parasuraman et al., 1988). Recent studies by Nesheli et al. (2015b) and Nesheli and Ceder (2014, 2015a,b) show that performance, information, tactic, and travel time are the main SQ attributes from the perspectives of the agencies and PT users alike, with interpretation to follow.

**Performance:** Fundamentally, in PT service delivery, performance is a key attribute of SQ (Watkins et al., 2015). There are a variety of performance measures that have been developed to describe different aspects of PT service. Kittelson et al. (2003) reported that, generally, PT users' greatest concerns are about issues that affect them directly, such as on-time performance issues. Studies show reliability linked to user perception of probability of on-time performance. Naturally, unreliable service results in negative user attitudes as uncertainty of travel time increases (Abkowitz, 1978, Bates et al., 2001). In a UK transit guide, it is reported that, on-time performance of local bus services is considered by passengers to be twice as important as scheduling frequency (Balcombe et al., 2004). Levinson (2005) demonstrates that reliable transit service is essential to attracting and retaining riders, especially in modern societies, where many transportation options are available.

On the other hand, Furth and Muller (2006) argued that traditional measures of service reliability such as on-time performance or headway regularity, as indicators of SQ, do not reflect the effect of reliability on passenger perceptions. They suggested that considering the real cost of waiting as a means of evaluating the effect of service reliability on passengers, would reveal a more accurate outcome. Accordingly, Iseki and Taylor (2009) argued that perceived waiting time by PT customers has been shown to be more onerous than the actual waiting time and is dependent on waiting conditions. Finally, the research

over the last decade indicates that performance reliability of the transportation system is a significant factor in the traveler's behavior of choice (König and Axhausen, 2002). Thus, in addition to improved passenger forecasting, a precise assessment of the behavior of passengers with respect to service performance can lead to overall improvements in mode and route choice prediction and transport model assignment (Recker et al., 2005).

**Information:** The other attribute of SQ in PT systems is information. High resolution information lends the traveler a sense of greater control over his trip, among other things with respect to waiting times, and affecting mode choice and perception of safety (Dziekan and Kottenhoff, 2007). Recent advances in smartphone technology are further facilitating more productive use of travel time (Lyons and Urry, 2005). Eboli and Mazzulla (2012) argued that a high quality information system is an essential factor in retaining existing riders and attracting potential users, and thus in increasing ridership. Studies (Bachok, 2007, Grotenhuis et al., 2007, Molin et al., 2009) show that integrated information systems are required to facilitate transfers between urban and interurban multimodal PT networks. Moreover, the recent study by Carrel et al. (2015) proposed a system to extract the personal transit travel diary of participants collecting location data with their smartphones by matching their location points to automatic vehicle location (AVL) data. The authors show that high-resolution information can be derived for travel times and their relationships with the timetable by identifying all out-of-vehicle and in-vehicle portions of the passengers' trips.

**Tactic:** It is increasingly evident that due to certain stochastic elements of PT systems (i.e., traffic disturbance, passenger demand fluctuation, and driver behaviors), pre-planned PT service is not always trustworthy at the operation level. One efficient approach to alleviating the uncertainty of PT services for correcting service irregularity in real time is to use selected operational tactics, such as holding, skip-stop, and short-turn. Studies (Hadas and Ceder, 2010a, Liu et al., 2014, Nesheli and Ceder, 2014, 2015b) show that applying certain operational tactics can significantly increase the number of direct (simultaneous) transfers and reduce total passenger travel time. Although there are more than a few studies on modelling PT real time control, consideration of passengers' perception associated with the implementation of operational tactics has been neglected. A few studies, such as Hanaoka and Qadir (2009) investigated bus passengers' behavior and perceptions associated with control action. The study describes an attitudinal on-board survey to understand respondents' behaviors in Bangkok. The

work focused on measuring the effects of a holding strategy using AVL technology in bus operation utilizing a simulation model.

**Travel time:** Clearly, travel time is one of the main factors for choosing a transport mode. Time savings often appear to be the greatest benefit of a PT system improvement. Fundamentally, travel time is related to the cost of time spent on transport, including waiting time (out-of-vehicle), running time (in-vehicle), and transfer time. Various studies show that travel time affects SQ (Hensher et al., 2003, Litman, 2008, Wardman, 2004). A recent study by Chowdhury et al. (2015) investigated the effects of travel changes which will induce a change in route choice by means of estimations for the reduction in travel time and travel cost. Their findings show that on average, for PT users to find routes involving transfers attractive, they sought at least a 25% reduction in their current travel time and at least a 10% reduction in their current travel costs. Likewise, this was dependent on different levels of comfort at the interchange.

## 9.5 Methodology

To develop a deeper understanding of SQ in a PT operation, the research design for this study is based on the conjoint analysis. The conjoint analysis concept has been applied in a number of studies of travel behaviors (Mackenzie et al., 1992, Reed, 1995). In conjoint analysis, a series of scenarios, or situations, each composed of various levels/attributes can be employed. The method allows us to evaluate the users' preferences (i.e., a realistic tradeoff between SQ attributes), and the establishment of an importance index based on par-worth (utility) for each attribute (Orme, 2010). Consequently, it is possible to compute the contributions of different independent variables to the dependent variable denoted by the overall evaluation scores. Generally, the conjoint analysis classifies the decision and judgment models (Hair, 2010). Essentially, the research outcome reflects the decision making process or the judgement model (Schaupp and Bélanger, 2005). The following section develops a conjoint measure to identify meaningful patterns and groups of users sharing similar opinions, decisions, and judgements.

### 9.5.1 Conjoint Analysis Instrument and Data Collection

In the design of the study instrument, a full profile approach for data collection, fitted to conjoint analysis is used. The full profile technique is suggested when the attributes are less than six (Hair, 2010). The four attributes of performance, information, tactic, and travel time are specified at three ordinal levels to construct the conjoint analysis. As explained in the previous section, these attributes have been developed through a comprehensive literature review and in an earlier attempt (Nesheli et al., 2015b). Table 9.1 shows the PT service attributes and levels used in this study. The attribute performance and its impact on the users' behavior are the focus under different levels of vehicle service reliability. The degree of service uncertainty was controlled through vehicle arrival status level. The scene to determine the usefulness of information was set by providing the various types of information from *offline info* to *accurate online-info*. To investigate the effect of real time tactics, some situations were set regarding selected real time control actions such as holding, skip-stops, short-turning, and short-cut. Our previous studies (Nesheli and Ceder, 2014, 2015a,b) show that each of these tactics has its own advantages and disadvantages for the travelers. Finally, as for travel time, the duration of travel for the user is considered. The levels were chosen to resemble the conditions of many PT commuter trips including direct trips or trips involving transfers.

According to full profile design, the attributes and their levels generate  $3^4 = 81$  profiles in total, which is not applicable when asking the respondents. To overcome this problem, fractional factorial design is used presenting a suitable fraction of all possible combinations of factor/attribute levels (Hair, 2010). The factorial design is based on the principle of orthogonally (orthogonal array) and is designed to find out the main effects for each attitude level (Addelman, 1962, Hair, 2010). Through the use of factorial design, twelve profiles are generated and each profile resembles a realistic situation for the PT user. The respondents are asked to consider these profiles (scenario cards) and rank them from 1 to 12, where 1 indicates excellent SQ, and 12 shows the worst SQ. The conjoint cards presented to respondents are divided into two trips, home-to-work, and work-to-home, to explore the effect evident from each trip.

The data was collected in Auckland, New Zealand (Case 1) and Lyon in France (Case 2) through an online survey and a street questionnaire in the main PT hub of these cities - the Britomart Transport Centre in Auckland, and the Laurent Bonnevey station in Lyon.

The same survey was conducted for these two different cases in two different cities in order to understand the various aspects of the study. Although each of the two cases presents a diversified user population, the characteristics of Lyon's PT system and its users' trip attitudes differ considerably from those of Auckland.

**Table 9.1:** Situational components employed in the conjoint analysis

Attribute	Level		
	1	2	3
Performance <sup>a</sup>	Vehicle arrives 2 minutes early	Vehicle arrives 2 minutes late	Vehicle arrives 10 minutes late
Information <sup>b</sup>	Offline info on departure-arrival times is provided	Approx. online info on departure-arrival times is provided	Accurate online information is provided
Tactic <sup>c</sup>	Holding the vehicle at some stops and you are on-board	Vehicle skips a stop and you are on-board	You are waiting at the stop and vehicle doesn't stop
Travel time <sup>d</sup>	Total of 15 minutes direct ride (to your destination)	Total of 25 minutes with transfer (to your destination)	Total of 35 minutes direct ride (to your destination)

<sup>a</sup> *Performance*: 2 minutes = a few minutes early/late, whereas 10 minutes=considerably early/late.

<sup>b</sup> *Information*: Offline info = printed timetable

Approx. online info = based on estimates and can range +/- 5 minutes.

Accurate online info = based on a decision-support tool using App on smartphones on actual vehicle arrival time, real time control action to be taken, and number of passengers on-board.

<sup>c</sup> *Tactics*: control actions to improve public-transport service, making it better than private cars in terms of travel time and comfort for all users involved. However, in some situations, it may increase your travel time.

<sup>d</sup> *Travel time*: Travel time starts when boarding the vehicle.

## 9.6 Results and Discussion

The survey was conducted between different groups. These groups differ in gender, age, employment status, and purpose of using PT services. On the basis of the total 300 expected respondents in case 1 and 2, a total of 122 were received, of which 118 were usable responses. This satisfies the overall response rate  $3(K - k + 1)$ , where  $K$  is the total number of levels across all attributes and  $k$  is the number of attributes (Orme, 2010). Our sample consisted of an almost equal response rate for both genders, with 7% more male respondents. Around 92% of the respondents in Case 1 and 90% in Case 2 were between 18 and 44 years old. A total of 63% of the respondents in Case 1 and



**Table 9.2:** Utility and importance index of the SQ element - Cases 1 and 2

Attribute	Level	Utility				Importance index			
		Case1		Case2		Case1		Case2	
		H-W	W-H	H-W	W-H	H-W	W-H	H-W	W-H
Performance	Vehicle arrives 2 minutes early	0.96	0.95	1.08	1.16	29.19	29.60	30.26	30.13
	Vehicle arrives 2 minutes late	0.30	0.27	-0.49	-0.55				
	Vehicle arrives 10 minutes late	-1.26	-1.23	-0.59	-0.61				
Information	Offline info	0.17	0.21	0.14	0.22	18.72	19.18	20.88	21.02
	Approx. online info	-0.10	-0.14	0.70	0.70				
	Accurate online info	-0.07	-0.06	-0.84	-0.92				
Tactic	Holding	0.89	0.86	0.49	0.45	29.33	28.33	23.47	22.91
	Skip-stops	0.47	0.42	0.32	0.28				
	No-service	-1.36	-1.28	-0.81	-0.73				
Travel time	15 minutes direct	0.65	0.72	0.99	0.99	22.77	23.89	25.39	25.95
	25 minutes with transfer	-0.11	-0.19	-0.58	-0.56				
	35 minutes direct	-0.54	-0.53	-0.41	-0.43				

Note: "H-W"=home-to-work, and "W-H"=work-to-home.

The constant value for all cases is 5.00.

77% in Case 2 are commuters and living in suburbs. Most of the respondents were either students (50%) or professional employees (45%).

### 9.6.1 Development of Conjoint Model

The overall results of the conjoint analysis are shown in Table 9.2. An analysis of utility values and an importance index of different attributes are performed in both cases based on home-to-work and work-to-home travel. The model description shows that both Pearson's  $R$  and Kendall's tau correlation between the observed and estimated scores are very close to one and their significance level is close to zero, representing goodness of fit for the utility values attained. The goodness of fit test is also verified at an individual level for the respondent. It indicates that individuals with poor predictive fit (i.e., 0.6 thresholds) should be identified for elimination from the analysis (Hair, 2010, Orme, 2010). All Pearson's  $R$  correlations were over 0.7 thresholds for both cases.

Inspection of the conjoint model utility in Table 8.2 reveals that both trip directions (i.e., home-to work and work-to-home) produce almost identical results and there are no

significant differences. Hence, it is possible to consider the effect of these trips on the comparable SQ. Clearly, the analysis indicates that from the respondent's perspective, performance is of the highest importance for SQ in both cases. The second most important attributes are tactics and travel time for Case 1 and Case 2, respectively. The attribute of information that accounts for 20% (on the average in both cases) of the total range of significance for utility, in the conjoint model, is the least important for SQ. The findings show that there are no significant differences between various levels of information. One of the main explanations for this, expressed by respondents during the survey, is the lack of a reliable application that passengers can rely on in real time. As a result, respondents are unable to determine a significant distinction between offline and online information.

On the other hand, by inspecting the utility function of each attribute individually, some useful and meaningful inferences can be made. For instance, in both cases, the utility for tactics when a passenger is waiting at a stop and the vehicle does not stop is -1.36, which is almost three times the measure for tactics when the vehicle skips a stop and the passenger is on-board. As a result, utilizing the tactics that lead to an increase in the passenger's out-of-vehicle waiting times is more destructive to SQ than the effect of those tactics which are associated with in-vehicle waiting times. Furthermore, reassuringly, the analysis shows that only total travel time is an important factor to the SQ. This indicates that users prefer a lesser travel time even with implications for their total travel experience.

Overall, it can be inferred that growing performance, tactic, and travel time will highly influence SQ and increase its levels and outcomes. Consequently, the best predictive models can be expressed as follows:

$$U_{SQ} = U_{Performance} + U_{Information} + U_{Tactics} + U_{Travelttime} + 5.00 \quad (9.1)$$

For example, in Case 1 based on the defined equation, the highest and lowest likely utility for an orthogonal plan, respectively, are:

$$\begin{aligned} U_{max} &= 0.96(2 \text{ min early}) + 0.17(\text{off-line info}) + 0.89(\text{holding}) \\ &+ 0.65(15 \text{ min direct ride}) + 5.00 = 7.67 \end{aligned} \quad (9.2)$$

$$\begin{aligned}
 U_{min} = & -1.26(10 \text{ min late}) - 0.10(\text{approx info}) - 1.36(\text{no-service}) \\
 & - 0.54(35 \text{ min direct ride}) + 5.00 = 1.74
 \end{aligned} \tag{9.3}$$

Evidently, any other utility value for SQ may present itself between the above limits and corresponds with the original ranks assigned by the participants. That is an assessment of any potential PT service scenario based on the above. Indeed, based on the proposed model with the components of performance, information, tactic, and travel time, a measure of SQ at the operational level could be assigned and scaled using the aforementioned range.

### 9.6.2 Clustering the results

Although the overall trend of the developed conjoint model depicts a rational pattern, deeper analysis may shed more light on passenger preferences and attributes, through considering data drawn from different response groups. This is possible as a result of responses having been subjected to a standard cluster analysis based on ranking of preferences and attributes by each individual from the outset. The cluster analysis is descriptive and non-inferential, such that it can be used as a confirmatory component for established groups and conceptual foundations (Hair, 2010). Table 9.3 shows the results of a hierarchical clustering procedure which is employed to create a complete set of cluster solutions. By this method, the classification ranges from all-single member cluster solutions to a one-cluster solution. In fact, the hierarchical framework enables the comparison of any set of cluster solutions (Hair, 2010). Subsequently, a separate discrete conjoint analysis is performed on the determined clusters to extract new utility values and importance indices. Figure 9.1 illustrates the variability of the attribute importance index for SQ as associated with the identified clusters. The results from Table 9.3 indicate that there are fundamentally different perceptions regarding what determines SQ. In Case 1, cluster 1 is the largest, and exceeds 40% of the total, hence having the greatest influence on the overall SQ. As shown in Figure 9.1, these respondents identify tactics to be the most important attribute for SQ, followed by performance and travel time as the main decisive attributes. In Case 2, on the other hand, cluster 3 (more than 49% of total) is dominant and has the most impact on the overall SQ.

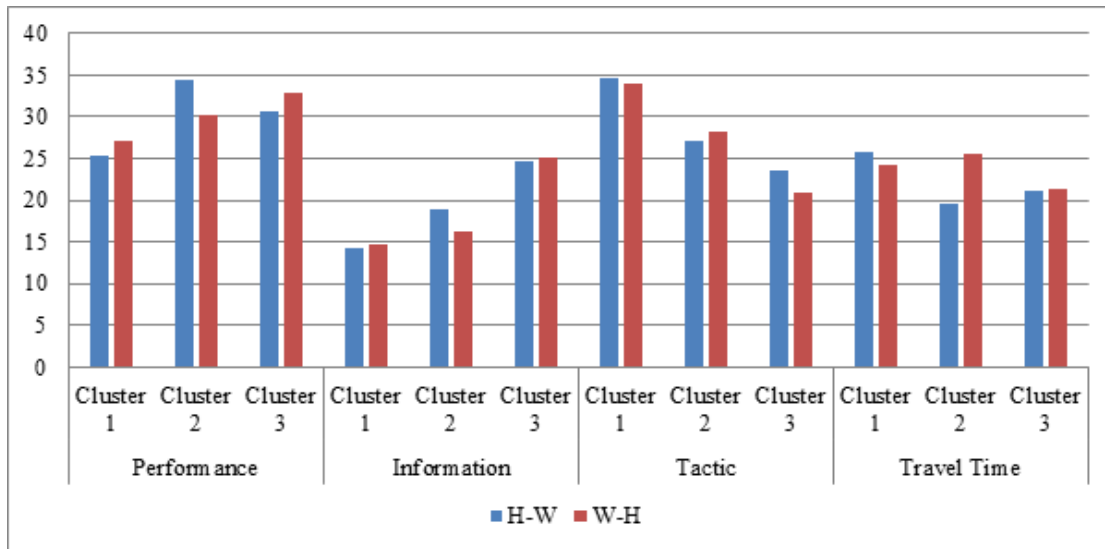
**Table 9.3:** Cluster results for Cases 1 and 2.

		Clusters	Frequency	Percentage	Cumulative Percentage
Case1	H-W	1	54	44.3	44.3
		2	29	23.8	68.0
		3	39	32.0	100.0
		Total	122	100.0	
	W-H	1	49	40.2	40.2
		2	39	32.0	72.1
		3	34	27.9	100.0
		Total	122	100.0	
Case2	H-W	1	35	29.7	29.7
		2	25	21.2	50.8
		3	58	49.2	100.0
		Total	118	100.0	
	W-H	1	33	28.0	28.0
		2	30	25.4	53.4
		3	55	46.6	100.0
		Total	118	100.0	

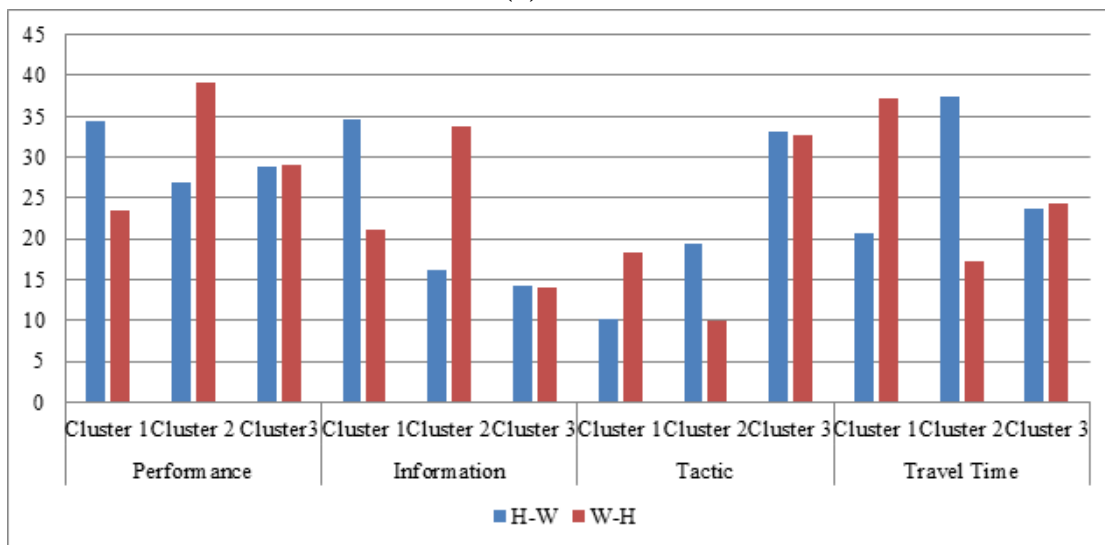
These respondents, as in cluster 1 for Case 1, regard tactics to be the most significant attribute for the SQ, with performance and travel time following. A precise look at Figure 9.1 reveals that information has the lowest effect on judgement of SQ in both cases. However, we can see that in Case 2, cluster 2 is radically different, and information becomes one of the most important considerations in perception of SQ (importance index of 33.7 for the work-to-home trip), though they also find performance important. In this cluster, tactic bears the least importance. Although information is an important attribute in any SQ, it is evident from the findings that greater influence is attributed, by a large group of people, to other SQ attributes. Conceivably, this may be related to the concern that the benefit to be gained from high resolution information is inadequate at the PT operation level. The inclination is to believe that more effort is needed to develop an integrated, real time information system to overcome the key shortcomings of current models and their usage (Carrel et al., 2015).

### 9.6.3 Overall PT Service Satisfaction

Finally, in order to understand the underlying criteria of users' preferences for and expectations of PT services, and for a proportional evaluation of five criteria for out-of-vehicle waiting time, in-vehicle waiting time, transfer time, overall (wait and ride)



(a) Case1



(b) Case2

**Figure 9.1:** Importance index of SQ factor identified clusters

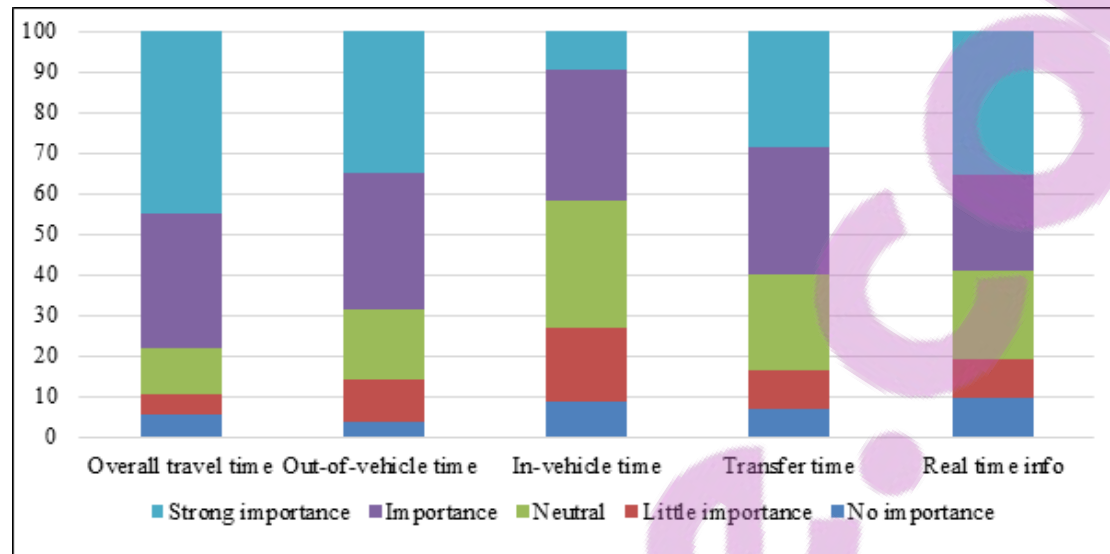
travel time, and high resolution real time information on the smartphone are given. Respondents from the two cities sampled were asked to rate their satisfaction with the overall reliability of PT service from 1 (no importance) to 5 (strong importance). As Figure 9.2 shows, the first thing to be noted is the similar tendencies in both cases, even if there is some variation in the ratio. The strongest importance is attributed to travel time (i.e., receiving a score of 5 is associated with overall travel time) by an average of 37% of the respondents in both cities.

Not far below that service factor, the high resolution real time information on mobile

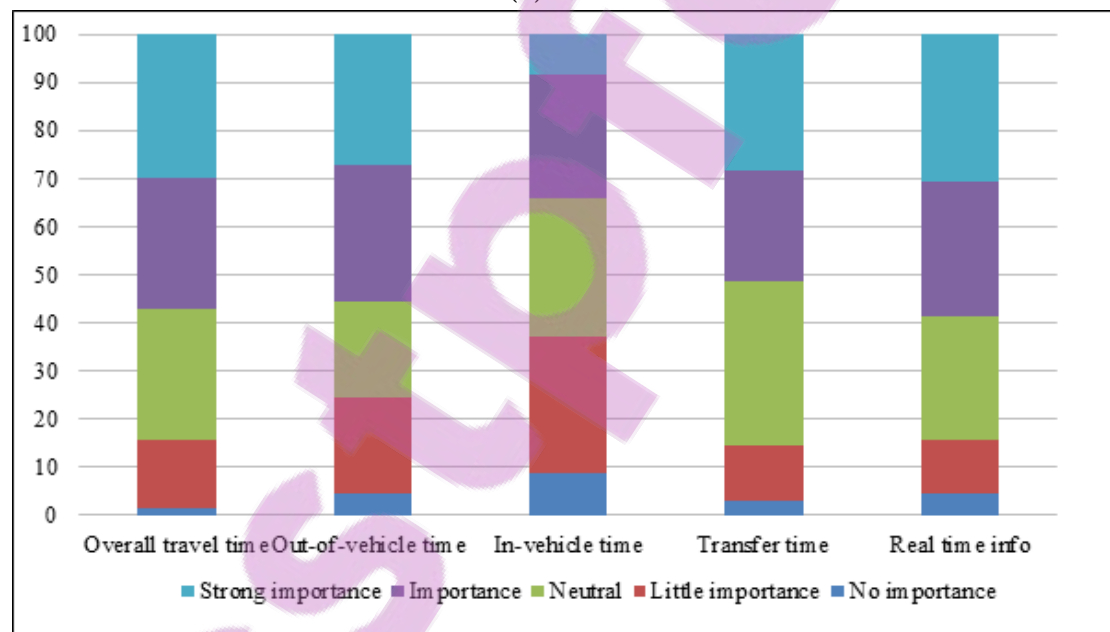
devices was of strong importance for 33% of the respondents on the average in both cases. This finding suggests that high resolution information could improve service satisfaction. Thus, providing reliable information may be the ultimate goal for advanced, efficient PT systems, but not a key factor for all SQ levels. On the other hand, the results reveal that there are indeed obviously different perceptions concerning out-of-vehicle, in-vehicle, and transfer waiting times. This also indicates that the marginal burden or disutility of out-of-vehicle waiting time is perceived to be significantly more burdensome than in-vehicle travel time. Different studies have argued this issue (Furth and Muller, 2006, Iseki and Taylor, 2009, Reed, 1995).

#### 9.6.4 Discussion

As demonstrated, there are many different means by which various groups of PT users evaluate SQ and judge it. Therefore, the preference criteria are not absolute, and the existence of different trends warrants consideration. However, it is evident from the findings that a large group of people from both cities sampled prefer the same attributes of performance and tactics as more decisive in SQ for PT systems at the operational level. Essentially, performance satisfaction combined with implementing proper control actions are seen as the driver of SQ development in the absence of which PT operations will suffer. It has been noted that SQ might be a progression of attributes such as performance, information, tactics, and travel time. This basic idea implies, in practical terms, that control actions and strategies might be implemented in a way that contributes to or strengthens other attributes of PT service operation quality. Therefore, within the identified judgment trends, a set of real time control actions (i.e., tactics) is proposed to strengthen the relation of SQ element perceptions and boosted perceptions, in general, to the operation SQ level. Employing these control actions such as holding, skip-stops, short-turning, and speed changes in an optimal manner would provide a more efficient service, reduced travel times, and more successful transfers. On the other hand, the differences between in- and out-vehicle waiting times which form PT users' perceptions are substantial in terms of considering how to utilize real time control actions. As a result, improvement of the effect of applying real time tactics on demand-side perceptions and decisions as complementary to the agent side beg being suggested. Significantly, this allows PT agents to provide PT users with different possible options, including



(a) Case1



(b) Case2

Figure 9.2: Satisfaction with the overall reliability of PT service

operational tactics, with real time information, thus enabling more efficient, reliable PT service operation to increase ridership.

## 9.7 Conclusion and Remarks

Understanding PT service quality cannot be achieved without understanding and considering the effect of implementing daily operational control methods associated with conventional attributes of PT service operation on the PT users' perceptions and decisions. To attain this goal and to assess the SQ elements, a user decision and preference survey was conducted to investigate passengers' attitudes and perceptions with respect to various PT operational situations. The SQ has been evaluated with four general factors of performance, information, operational tactics, and travel time. A conjoint analysis coupled with cluster analysis has been developed to capture the most important factors in evaluating the SQ process. To assess the differences, the same survey was conducted in two cities with different characteristics: Auckland, New Zealand and Lyon, France.

The findings of utility values for each attribute level and factor importance indexes in both Auckland and Lyon indicated that there are no meaningful differences between the two trip directions (i.e., home-to-work and work-to-home) and they produce almost similar results. The results depict a performance element for both cities as the most influential attribute, exceeding 30% compared to the degree of impact of tactics in Auckland (around 29%), and travel time in Lyon (25%). For both cities, the same level of importance is attributed to information, just around 20%. The analysis also reveals that all the chosen attributes are important and no single attribute is undervalued in the overall decision making procedure.

Consequently, cluster analysis was used to classify the respondents in order to check if the overall results were indicative of a general consensus among PT users, or, alternately, if there were different perspectives on what constituted SQ. Three clusters of preferences were identified among respondents by hierarchical cluster analysis. By means of a second round of conjoint analysis, the decision criteria for the three clusters were observed. The largest clusters in both cities judged the SQ mainly by tactics and performance, followed by lesser importance attributed to travel time. For these clusters, information is the least decisive. However, for both cities, the analysis shows that the impact of



high resolution real time information on the overall satisfaction was reasonably strong, reflected by the highly important significance attributed to it by around 33% of the respondents (on the average). Such a finding provides a powerful conceptual lens through which reliable information on modern PT operation can potentially capture the essence of the relationship between its effectiveness and various elements of SQ incurred as a result of its deployment in an advanced, efficient PT system.

Furthermore, it is revealed that the marginal burden, or disutility, of out-of-vehicle waiting time is perceived to be significantly more burdensome than in-vehicle travel time. Hence, for developing any tactic model intended for users experiencing out-vehicle time, more weight should be given to the penalty function of the tactic, and operators should be attentive to this fact when they consider using such a tactic.

The limitation of this study is that the results presented cannot demonstrate strong conclusions, but it clearly demonstrates a tendency. The inferences made in this study are specific to the PT system of Auckland, New Zealand and Lyon, France. However, we believe our study to be a start in developing our understanding of SQ by PT systems at the operation level, by implementing real time operational tactics. A more comprehensive and accurate study could show the attributes, the case, and the kind of passenger, for whom it could be effective to propose improved SQ of PT operations. Future research may continue to improve the modelling of SQ judgment by different PT users groups and its sensitivity to different operational tactics.

## Chapter 10

# Summary, Conclusion and Recommendations

This chapter provides a concise summary of the research findings based on the objectives and research problems outlined in [Chapter 1](#). These findings are presented using the thesis's three main categories: operational, environmental and demand aspect. Finally, this chapter portrays the future research expected.

### 10.1 Summary of the Thesis

In contemporary society the public transport (PT) system is usually involved into a complex urban area in which any change of its operation may have economic, environmental and social impacts. It is increasingly evident that one of the most challenging problems of policy makers is shifting a significant number of car users to PT in a sustainable manner. Ceder (2007, 2015) suggests that an important consideration in the effort to retain existing users and attract new passengers is to improve serviceability by offering routes with seamless transfers. Notably, one of the common strategies for increasing the efficiency of a PT system and making it reliable is utilizing real-time control actions (tactics). Accordingly, in this thesis our overall objective is to develop theoretical, computational and generic approaches of the challenge to make it possible to control, in real-time, selected moving elements in a PT network with random variables, and maximize their encounter probability.

In order to capture these heterogeneities of research approaches a "Library of Tactics" has been adopted enabling us to maximize the number of successful connections between PT vehicles, improving PT operation reliability, providing continuity between users' preferences, and reducing adverse environmental impacts. Intuitively, employing advanced technologies (e.g., GPS, automatic vehicle location, real-time information) through the implementation of operational real-time tactics such as holding the vehicles, skipping-stops, speed changes, boarding-limit, and short-turning in an optimal manner, provides a "real-time" solution for responding to system's deterioration. This approach will inevitably help the society to develop a reliable, green, efficient, and attractive PT system.

The core of the operational aspect was to develop an efficient optimization algorithm (using operation research techniques) to solve the problem in a real-time fashion. The model has been tested, using simulation models, for a real-life case study in Auckland, New Zealand from which promising results were attained for implementation in practice. The environmental aspect covers a design of a life cycle assessment process. The analysis showed that applying appropriate real-time PT tactics leads to a meaningful reduction in total global warming per day.

The PT passenger demand aspect dealt with determination of user's decisions and preferences for situations characterized by the use of real-time tactics. Passengers' behaviour was investigated using survey studies. It was found that the extra times tolerated for all the tactics is dependent on the characteristics of the site-specific PT service. In addition PT service quality found too to impact passengers' behaviour when using real-time operational tactics. The analysis showed that performance, information, tactic, and travel time were the main service-quality attributes to impact this behaviour. Generally speaking, the research findings of this thesis provide an opportunity to address key policy-related PT issues. Two of such issues are discovery of ways to increase the satisfaction of the PT users and finding ways to reduce CO<sub>2</sub> emissions and air pollution.

## 10.2 Main Research Findings

This research proposes new modelling and methods for developing optimal real-time tactics and strategies to attain a reliable PT service. In doing so it doesn't only extend the state-of-the-art of the research of this theme, but also deliver guidelines on

how to attain a better PT service to PT agencies and policy makers. The development and ways to materialize an implementation of a "Library of Tactics" provide new insights to create a more advanced PT system reflecting a further efficiency and integration of a multi-modal PT operation.

*Following are the main research contributions accomplished in this thesis.*

The **Chapter 2** formulated and tested the selected operational tactics: holding, skip-stop and skip-segment by three scenarios: no-tactics, holding and skip-stop, and holding and skip-segment; the two latter scenarios are combined operational tactics. The implementation of the concept was performed in two steps: optimization and simulation. The optimization searched for the best combination of operational tactics. The simulation served as a validation of the optimal results under a stochastic framework. The results demonstrated if, for instance, some stops are close to each other and only a very few passengers will be impacted from skipping those stops; the skip-segment tactic can take place as compared to the skip of individual stop tactic which has the limit that no more than one stop can be skipped in a row. Further findings are as follows:

- The significantly better results achieved for the holding and skip-segment combined tactic than for the holding and skip-stop combined tactic especially for short headway cases.
- By using the combined tactics, compared with the no-tactics scenario, a considerable reduction of total travel time is attained.
- When the schedule deviation tends to zero, the maximum saving of total travel time occurs without the use of any tactics; this max travel time saving coincides with max numbers of direct transfers.
- Passengers waiting for a late bus prefer, in the short headway cases, and for a not so late and not so ahead-of-time bus, in the long headway cases, to continue to wait than to find an alternative solution (walking or use of another travel mode); a behaviour that makes it worth applying the combined tactics.

The study presented in **Chapter 3** discussed original mathematical programming formulations for three real-time control strategies, or policies: holding, skip-stops, and

short-turning. The proposed model was evaluated in a stochastic simulation environment under different schedule-deviation conditions (events) that could highlight when control policies improve the system's performance. An agent-based simulation framework was built to represent a real-life example and to generate random input data for the proposed optimization model. Based on the formulations for optimization and the simulation framework, an efficient algorithm for combining all control actions selected was developed. Further findings are as follows:

- The results demonstrated that the effectiveness of combined tactics is higher than that of any binary type of control. Thus, combining all control tactics leads to an increase in direct transfer of up to 153% and a reduction in total passenger travel time of 4.7% on average for all scenarios.
- In general, the short headways yielded the best results, compared with long headways.
- A considerable reduction in total travel time was attained in scenarios having no large schedule deviations. The finding confirmed the outcomes of [Chapter 2](#).
- A holding and short-turning policy in a larger schedule-deviation scenario exhibits better performance than a holding and skip-stops policy.
- The increase in passenger travel time stemming from the use of operational tactics was usually less than 1%.

In [Chapter 4](#), besides the reliability of the PT system, the effect of each tactic on system performance was also investigated. System reliability is represented by schedule deviation, which was calculated across all bus trips at the control stops. System efficiency was represented by the effect of using different tactics on each bus trip for different events. The most important outcome, which has been proved by the case study presented, was that the system's performance was enhanced by up to 58% with the aid of a proper combination of tactics in the right state at the right time. Thus, the study achieved five important contributions: 1) it introduced a simplified analysis for measuring PT system performance; 2) it proposed a PT system deterioration and repair model; 3) it developed an agent-based simulation model; 4) it enabled a new method for sensitivity analysis of total passenger travel time, different strategies, and headways and their effect on the

system; and 5) it made it possible to simulate what-if scenarios, such as change of demand because of unexpected passenger overflow, different combination of operational tactics and minor changes in the transit network in real-time. The further findings are as follows:

- The skip-stop tactic is sensitive to headway and total passenger travel time. Thus, operators should pay attention to this fact when they consider using such a tactic, especially for long headways and with higher total passenger travel time.
- Significantly better results were attained for the holding tactic when the total passenger travel time was low.

The study presented in [Chapter 5](#) adapted a real-time control methodology to attain optimally real-time control actions so as to minimize the bunching phenomenon. The study used simulation tools in order to identify optimal settings by which a combination of holding and speed-changes tactics could be efficiently implemented. The main findings are as follows:

- The proposed control strategy always results in a significant lower standard deviation of the scheduled headways than the no-control strategy.
- The results showed a better outcome of reducing headway variations for Scenario 1 (base-demand) than Scenario 2 (high-demand).
- Applying semi-control strength in Scenario 2 resulted in a significant lower passenger waiting time than the no-control strategy. For Scenario 1 the semi-control and full-control strengths yield close results.
- Vehicle bunching situations were reduced significantly by the use of the operational control tactics.
- The control tactics using Scenario 1 exhibited smaller average cycle time and lower variability of the reliability measures than when using Scenario 2.
- The developed combination of operational tactics was sensitive to changes of passenger demand at high-demand levels; this was related to changes in reducing passenger wait time, in-vehicle time, transfer waiting time, number of bunching situations and vehicle cycle time. In other words, operators should pay attention

to the level of passenger demand when using operational tactics, especially with full-control strength.

The study presented in [Chapter 6](#) formulated and examined three control policies: no-tactics, holding and boarding-limit, and holding and skip-stops under two scenarios: high frequency and medium frequency services in headway-based PT system. This chapter is a continuation of [Chapter 5](#) especially in terms of utilizing event-based activity simulation analysis framework. The main findings are as follows:

- If possible, a combination of tactics should be applied to attain a considerable reduction in additional passenger travel time, and to outperform reliability in meeting vehicles at transfer points. Holding tactic for earliness, boarding-limit or skip-stops tactics for tardiness are quite beneficial with respect to control effectiveness.
- Holding and boarding-limit policy in high frequency service yielded the better result. On the other hand, holding and skip-stops policy exhibit better performance in medium frequency service.
- Compared with a no-control situation, the control policy presented showed that not only the expected additional total travel time was reduced (on average by 61%), but it also outperformed other control schemes in terms of reliability in meeting vehicles at transfer points.
- A considerable reduction in direct transfers was attained in holding and skip-stop control policy. This indicates that this control policy is fairly robust to increase the likelihood of direct transfers.

The study presented in [Chapter 7](#) investigated the benefits of implementing a real-time operational tactic scheme for the purpose of reducing the environmental impacts of PT systems. Using life cycle assessment (LCA), has shown that by applying the proposed control model a 5.6% reduction in total global warming potential (GWP) per day was attained compared with the no-tactic scenario. The transport process is computed by means of the GaBi dataset. The methodology introduced in this chapter has a wide range of applications for PT systems in different geographic settings.

The study of Chapter 8 was undertaken in two-parts: (i) an assessment of the effects of delay on PT users' perceptions and decisions to change route or mode; (ii) an evaluation of users' decisions based on various real-time operational tactics. To attain the objectives of the study, a user-decision and preference survey was conducted to investigate users' attitudes toward various control actions. To assess the differences, the same survey was conducted in two cities with different characteristics: Auckland in New Zealand and Lyon in France. A statistical analysis was carried out, and decisions models were built using both multinomial logistic regression (MLR) and a decision tree (DT)-based method. The main findings are as follows:

- In certain situations (e.g., waiting at a stop more than 10 minutes), more than 60% of the travellers would change their decision and adapt their travel behaviour on the basis of such a decision-support tool.
- Both models (MLR and DT) demonstrated that the most significant predictor impacting on a traveller's decision is delay time. Some other factors, such as the purpose of trip, transfers, travel time, an even age of users, also have an impact on passenger's decision.
- To complete the guideline, tolerated time models using real-time tactics were developed.
- The tolerated time, for certain event would find the study informative in suggesting operational tactics according to the outcome desired.
- The extra times tolerated for all the operational tactics depend on the characteristics of the PT service, which differ between Auckland and Lyon; on the average, it is between three and nine minutes at both cities.
- The results showed that although the waiting-time tolerated can be compensated by giving a bonus to users, it is difficult to do so with the extra walking time.

Finally, in [Chapter 9](#), the PT service quality (SQ) was evaluated with four general factors of performance, information, operational tactics, and travel time. A conjoint analysis coupled with cluster analysis has been developed to capture the most important factors in evaluating the SQ process. To assess the differences, the same survey was



conducted in two cities with different characteristics: Auckland, New Zealand and Lyon, France. The main findings are as follows:

- For each attribute level and factor importance indexes in both Auckland and Lyon indicated that there are no meaningful differences between the two trip directions (i.e., home-to-work and work-to-home) and they produce almost similar results.
- Performance element for both cities as the most influential attribute, exceeding 30% compared to the degree of impact of tactics in Auckland (around 29%), and travel time in Lyon (25%).
- For both cities, the same level of importance was attributed to information, just around 20%.
- All the chosen attributes were important and no single attribute was undervalued in the overall decision making procedure.
- The largest clusters in both cities judged the SQ mainly by tactics and performance, followed by lesser importance attributed to travel time. For these clusters, information was the least decisive.
- It is revealed that the marginal burden, or disutility, of out-of-vehicle waiting time is perceived to be significantly more burdensome than in-vehicle travel time. Hence, for developing any tactic model intended for users experiencing out-vehicle time, more weight should be given to the penalty function of the tactic, and operators should be attentive to this fact when they consider using such a tactic.

Figure 10.1 illustrates the main contribution of each chapter and the research objective.

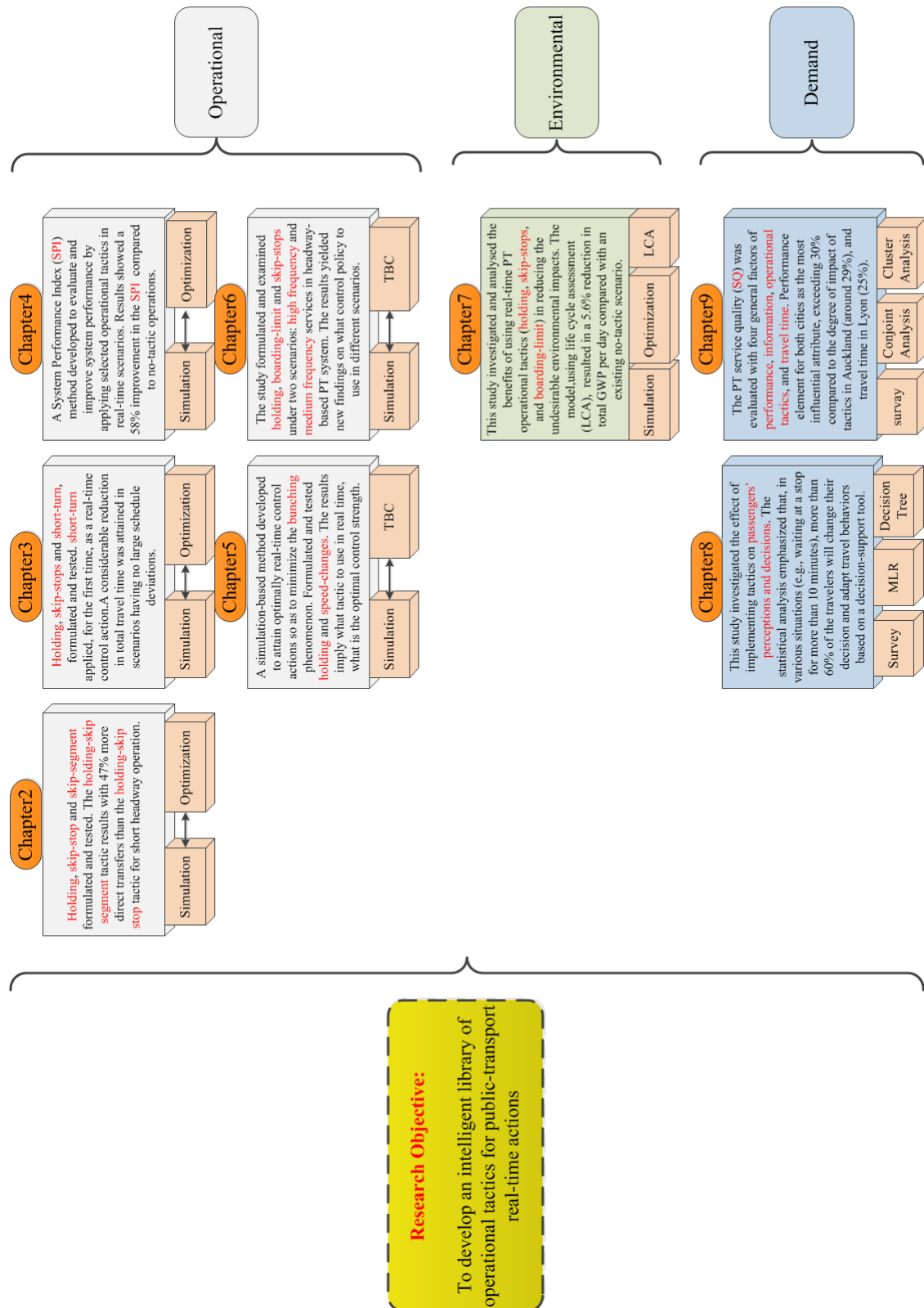


Figure 10.1: The main contribution of each chapter.

### 10.3 Limitations

Data collecting required to illustrate and to validate the optimization, simulation and statistical analyses represents a significant challenge. These challenges stem from the restrictions existed in providing these data sets from the perspectives of privacy, ethical, security and commercial-related sensitivity. A further limitation has to do with the use of passenger demand only from two locations: Auckland, New Zealand and Lyon, France. Other limitations are related to the assumptions used for constructing each model.

### 10.4 Future Research

Future research may continue to advance the library of operational tactics in terms of categorization, configuration and representation of this library based on other research areas. Harnessing newly available 'Big-data' and recent advancement in communication technologies make it possible to research for a general theoretical framework to represent the optimal real-time decisions required for PT operations. Although this study is PT-related the proposed concept has a potential to be applied to similar problems of logistics where freight can replace PT passengers. Finally the following suggestions provide a further future research directions to improve the proposed concept of this thesis.

- (a) The development of a ready-to use decision-support tool to provide information before implementing any control actions, and weighting the quality of transfers in an optimization model for different transfer types.
- (b) Extension of the methodology to evaluate the implications of real-time control tactics and strategies on the inter-modal and multimodal transport systems.
- (c) The development of an extended list of operational tactics within the considered library of tactics, and investigate further scenarios of passenger demands, driver behaviour, and network characteristic.
- (d) The development of a more strategic and economic-based study to assess the benefit of using real-time operational tactics
- (e) Implementation of the LCA methodology to evaluate other environmental factors, including: acidification, eutrophication, and ozone-depletion.

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- (f) The development of methodology and analyses to evaluate the full environmental and cost benefits of retrofitting local bus services with control systems for applying real-time tactic based control.
  - (g) Extension of the methodology to integrate with other studies of risk perception and psychometric modelling to examine the framework of the process behind passengers' decisions.
  - (h) Extension of the modelling of SQ judgment by different PT users groups and its sensitivity to different operational tactics.



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